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[illegible] Gravity Gradiometer Survey System (GGSS) Program

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The GGSS program began in early 1983 with the objective of delivering a land-mobile and airborne system capable of fast, accurate, and economical gravity gradient surveys of large areas anywhere in the world. The objective included the development and use of post-mission data reduction software to process the survey data into solutions for the gravity disturbance vector components (north, east and vertical).

This document describes the GGSS equipment hardware and software, integration and lab test procedures and results, and airborne and land survey procedures and results. Included are discussions on test strategies, post-mission data reduction algorithms, and the data reduction processing experience. Perspectives and conclusions are drawn from the results.

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TABLE OF CONTENTS

1.0 INTRODUCTION

The Gravity Gradiometer Survey System (GGSS) was designed, built, and tested by Bell Aerospace Textron under contract (No. F19628-83-C-0052) from the Air Force Geophysics Laboratory with funds from the Defense Mapping Agency. DMA initiated this procurement to acquire a quantum leap in gravity surveying capabilities needed to support current and future DOD systems requirements for accurate gravity disturbance vector charts.

The program began in early 1983 with the objective of delivering a land-mobile and airborne system capable of fast, accurate, and economical gravity gradient surveys of large areas anywhere in the world. The objective included the development and use of post-mission data reduction software to process the survey data into solutions for the gravity disturbance vector components (north, east and vertical).

This document describes the GGSS equipment hardware and software, integration and lab test procedures and results, and airborne and land survey procedures and results. Included are discussions on test strategies, post-mission data reduction algorithms, and the data reduction processing experience. Perspectives and conclusions are drawn from the results.

2.0 PROGRAM OVERVIEW

Knowledge of the earth's gravity field is incomplete both in terms of global extent and over the full range of significant spatial frequencies. The primary sources of our current knowledge of earth gravity are:

- Low altitude satellite orbit perturbations, observed by tracking stations, have been used to estimate the low order, (up to about the 20th harmonic degree and order) spherical harmonic components of the gravity field. This so far is the only data having global coverage.

- Satellite altimetry (Seasat, Geosat) used to measure the ocean geoid extends gravity field knowledge over ocean areas out to about the 180th harmonic degree (200km & wavelength).

- Surface ship gravimetry can define wave lengths down to about 10KM wave length but at 15 knot survey speed coverage of the ocean is not complete.

- Over land areas static land gravimeter data is used along with a much smaller set of astrogeodetic observations. Accurate determination of elevation limits the precision of this data. Utility of this data is limited by:

    - Cost of the observations.

    - Confined to accessible land areas (polar regions, jungles, mountains, unfriendly countries are not accessible).

- Attempts have been made to collect airborne gravimeter data with only limited success due to exacting navigation requirements stemming from the inability of the gravimeter to distinguish between gravity, and acceleration (the equivalence principle).

A fully integrated airborne gradiometer/gravimeter/GPS system would be the most rapid efficient and economical way to expand our knowledge of the earths gravity field. The system would be capable of measuring over the range of wave lengths from 700KM to 2KM and be usable over both land and sea areas including otherwise inaccessible polar, mountainous, and jungle regions.

Given successful operation of the gradiometer on surface ships, it remained to demonstrate operation in the less benign airborne environment. This together with flight worthy gravimeter and with GPS approaching operational status provides the essential major elements of an economical airborne survey system.

The GGSS program has tested the gradiometer in a land vehicle as well as airborne. The function of land vehicle gradiometry is to densify astrogeodetic observations. In the GGSS program it also provided an economical means for debugging and grooming the system prior to costlier airborne testing.

2.1 Objectives

Demonstrate the feasibility of the gravity gradiometer as a gravity field survey tool. In particular for an airborne mapping pattern flown 600m above average terrain and consisting of two sets of orthogonal tracks with 5km track spacing and 300km length, demonstrate disturbance vector estimation accuracy for spatial frequencies higher than .002 cycles/KM as follows

- Deflection error of 0.18 are seconds RMS in each component.
- Gravity anomaly estimation accuracy of 0.9 mgal RMS.

The land vechicle starts at an astrogeodetic point and traverses to a second known astrogeodetic point. Using the values of the disturbance vector at the two end points and gradiometer measurements between them, estimate the disturbance vector along the route. Although definitive objectives were not specified, a tentative objective for a 100km route is an estimation error of 0.9 mgal RMS for each component of the disturbance vector.

2.2 Approach

Prior to testing, a number of system calibrations were carried out. As circumstances required recalibrations were carried out during the testing. The major calibrations were;

- GGSS platform inertial instruments.
  - Gyro - Bias, scale factor, and alignment angles.
  - Accelerometer - Bias, scale factor, and alignment angles.
- Gravity gradiometer instrument - scale factor and alignment.
- 5th wheel navigation - scale factor and platform synchro offsets.
- GGSS gimbals, frame and van combined self gradient.
- GGSS gimbals, frame, van and aircraft combined self gradient.

The GGSS testing was carried out in two phases for both the land vehicle and airborne configurations. Phase I was conducted in Western New York because of its convenience to Bell Aerospace facilities. Initial testing consisted of hardware and software debugging missions. The major thrust intended for phase I was repeat track testing to establish the performance of the gradiometer in a land vehicle and aircraft environment. The idea behind repeat tracks is that signal output should repeat and therefore differences between repeat tracks reflect instrument error or environmental sensitivities. Because of schedule problems, repeat track testing was deferred to the phase II testing site. Due to weather conditions at the end of the phase II testing schedule suitable repeat track airborne data was never flown.

Phase II testing was carried out in the Oklahoma Texas panhandle, selected for its relatively flat terrain, good GPS coverage, "good" flying conditions and for its active geology giving rise to strong gravity anomaly features. The purpose of phase II was to conduct operational surveys with the land and airborne configurations. As such this phase tested not only the gradiometer instrument, but also the survey design and other operational aspects of conduct of a survey, as well as the post mission processing of survey data.

A set of astrogeodetic points surveyed by DMA were made available to use as long wavelength tie points or as truth data points. Static gravimeter data in the form of 5' x 5' means were also used by DMA, AFGL and TASC to evaluate test data results. The astrogeodetic points, the land testing and airborne testing were all encompassed in the same 300KM square so many of the astro-geodetic points could be used to support both the land and airborne testing. Land vehicle surveys at the astrogeodetic points were intended for use in the upward and downward continuation of the gravity field solutions between flight altitude and ground level.

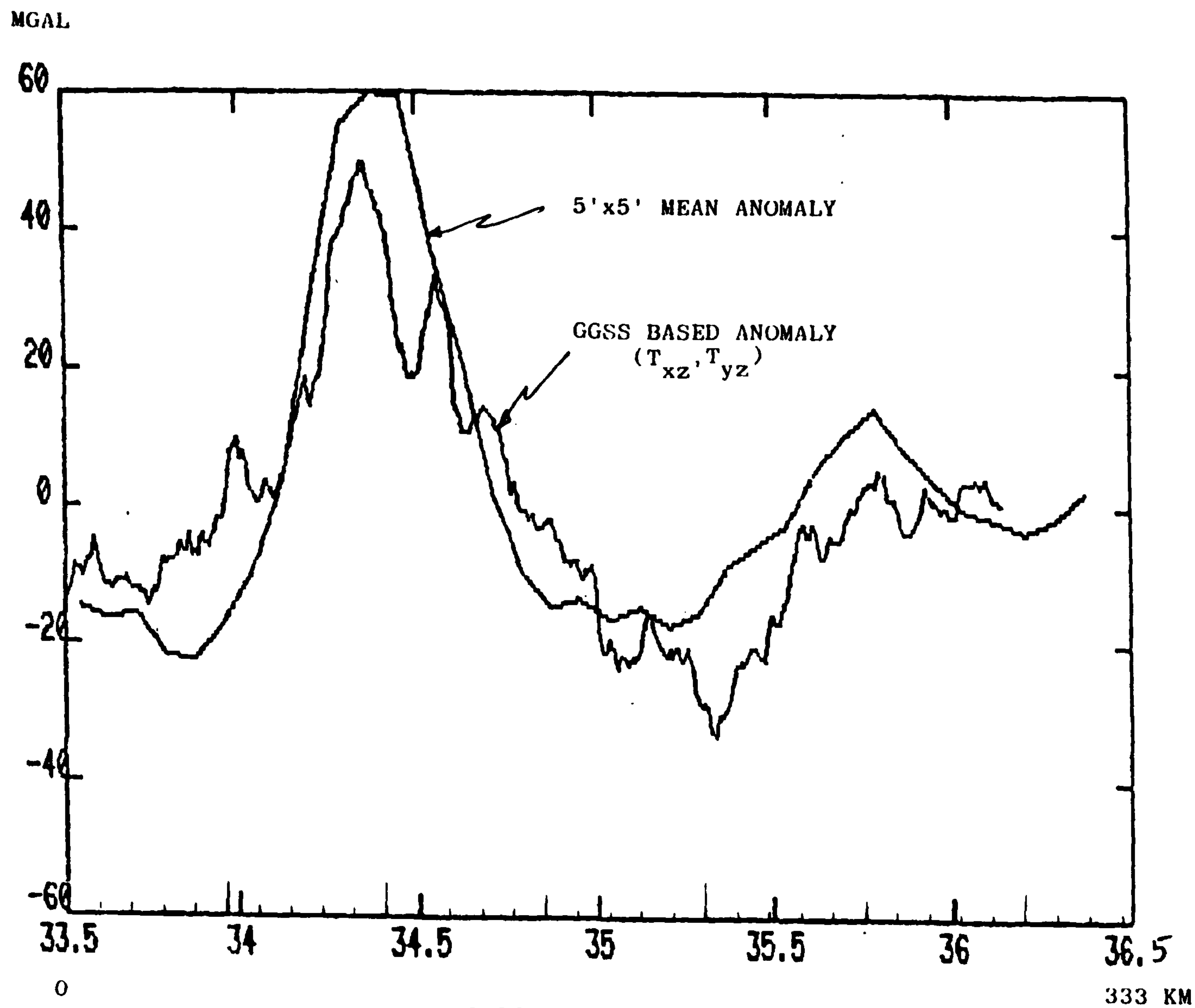
The airborne survey pattern was a 315KM square with parallel tracks spaced 5KM apart and flown nominally in both the north-south and east-west directions. Selection of end points for each track was based on a DMA supplied map projection relating the survey pattern to geographic coordinates. A geodetic track defined by the GPS computer was flown between these end points.

2.3 Summary of Results

Although the airborne test program was not a complete success, a significant milestone achieved was to demonstrate that the gradiometer can operate successfully in an airborne environment. Evidence of this is shown in Figures 2-1 and 2-2 which show the results of an analysis carried out by AFGL. These figures show the gravity anomaly along two north south tracks based on stage I post mission processing of gradiometer output data compared with 5' x 5' mean anomaly data. GGSS bias and trend were removed from each GGSS output and the result was then integrated (unconstrained by gravity field modeling) to give the gravity anomaly. Analysis of the difference between these curves shows about 9 and 11 mgal RMS for Figures 1 and 2 respectively. Neither of the curves shown in these figures represents the true value of gravity. The error associated with the 5' x 5' mean curve has not been quantified but probably falls in the range from 3 to 5 mgal RMS.

According to AFGL report "Analysis of Airborne Gravity Gradiometer Survey Accuracy", C. Jekeli, May 1984, the theoretical accuracy for anomaly estimation accuracy based on gradiometer data is 11.9 mgal for the following conditions (see ref 1).

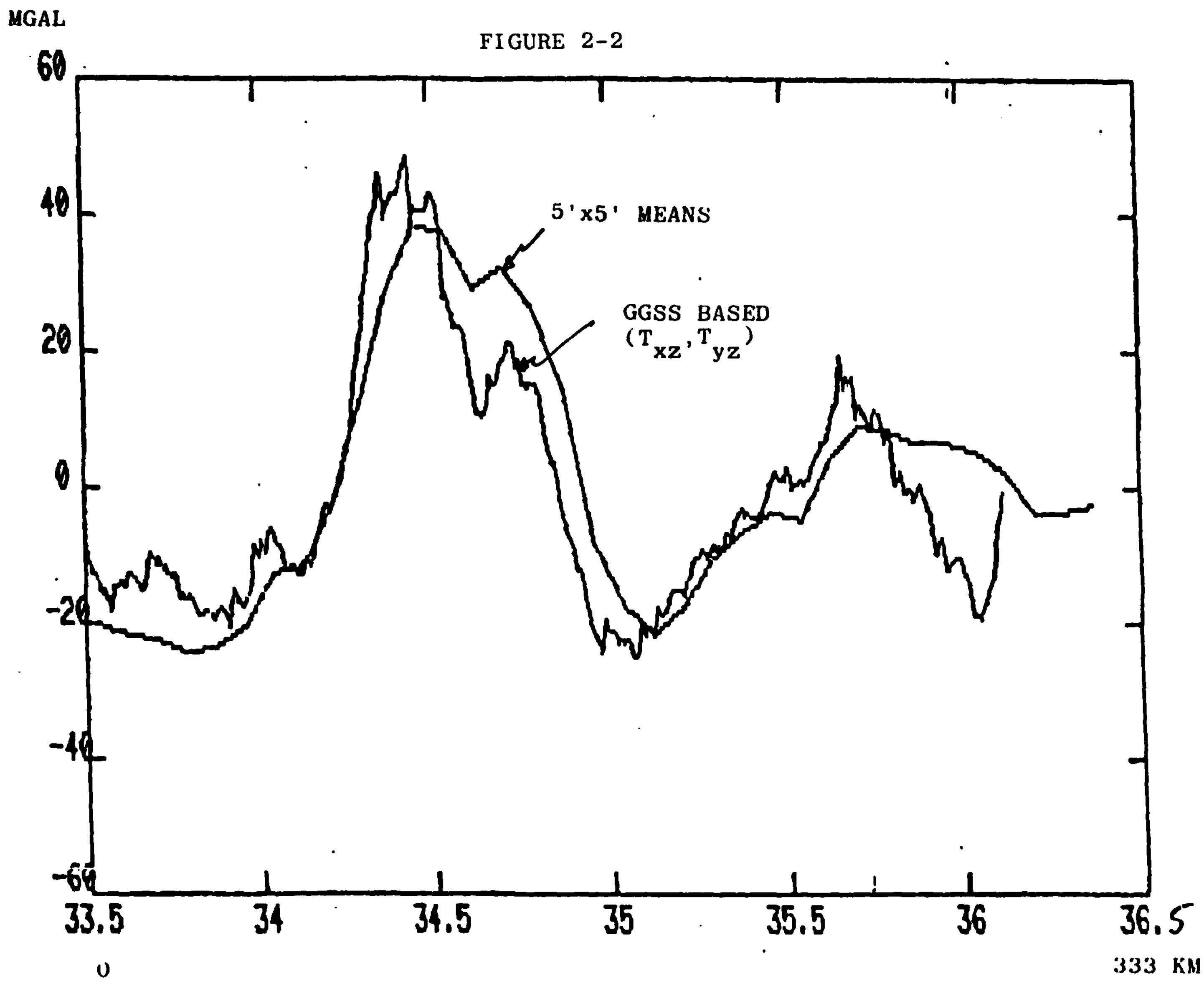
- Single track measurement of Txz
- 300KM/hr velocity at 600m altitude
- Low frequency cut off $w_o = \frac{2\pi}{500}$
- Gradiometer noise PSD = $\frac{.00017}{W^{1.6}} + 35 \quad \frac{E^2}{hz}$
- 3rd order markov gravity field model.



LATITUDE
TEXAS OKLAHOMA TEST
TRACK NS 41

FIGURE 2-1

FIGURE 2-2



LATITUDE
TEXAS OKLAHOMA TEST
TRACK NS39

In view of this theoretical result the test track data is reasonable.

Achieving the specified 0.9 mgal accuracy involves using all 6 GGI measurements, performing model constrained integration along track, and utilizing data from two orthogonal sets of parallel (5KM spaced) tracks.

Due to time and schedule constraints only part of the phase II van test data was analyzed. Figure 2-3 shows the road network and astrogeodetic point locations in the test area. The land data analyzed consisted of two repeat southbound traverses of a 33 mile stretch from astro location #7 to astro location #9. The test procedure for controlling gradiometer bias was not followed consequently it was necessary to use the disturbance vector values at all three astro points (#6, #7, and #9) for initial conditions and for determination of gradiometer biases leaving no astrodata for evaluation purposes. Also the procedure for handling terrain was not followed and straight integration of gradients was carried out instead of model constrained integration to obtain disturbance vector solutions along the track. The 5' x 5' mean data is not detailed enought to serve as reference truth data so all that is left as indication of performance is repeatability of the disturbance vector solutions on the two traverses. Figures 2-4A and 2-4B shows that for T_z the repeatability between the two passes is 1.3 mgals RMS with remarkable correlation of the high frequency variations. Figures 2-5A and 2-5B shows the Ty solutions on the two passes, the agreement is 4.0 mgal RMS. Figures 2-6A and 2-6B shows a comparison of the T_x solutions which show very poor agreement over the long term but very good over the short term. It is evident from an inspection of this data that a step of about 21.3E occurred at the 9KM point which happens to correspond with the turn from east to south between astro points 7 and 6. A second step of 6.9E occurs at about the 27KM point *(close to a road intersection)*. Inspection of the data shows a number of smaller steps and impulses occurring in the gradient signals. The possible sources of this behavior might be platform control problems, self gradient compensation problems, vibration or simple acceleration sensitivity. This problem is currently being investigated on land vehicle testing in WNY.

Much of the Oklahoma airborne data was judged poor or non usable. A number of possible causes have been identified;

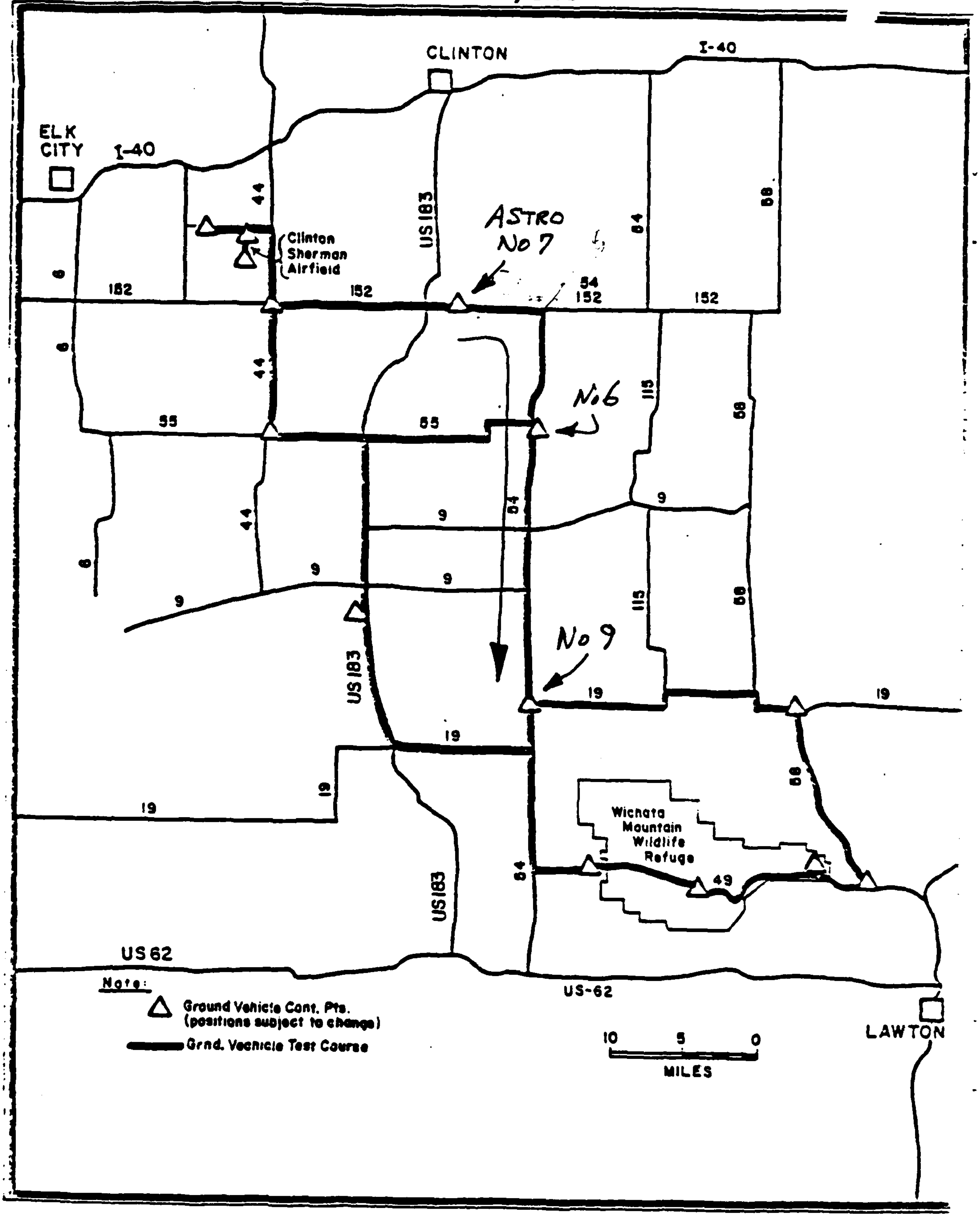
- Tests conducted after the GGSS phase II tests were completed, revealed that the vertical gyro drift was stepping intermittently. Observations made during shakedown testing suggest that this condition existed throughout the GGSS tests. This condition led to erroneous calibration results and probably caused platform control problems during the testing. Replacement of this gyro resulted in markedly improved platform performance.

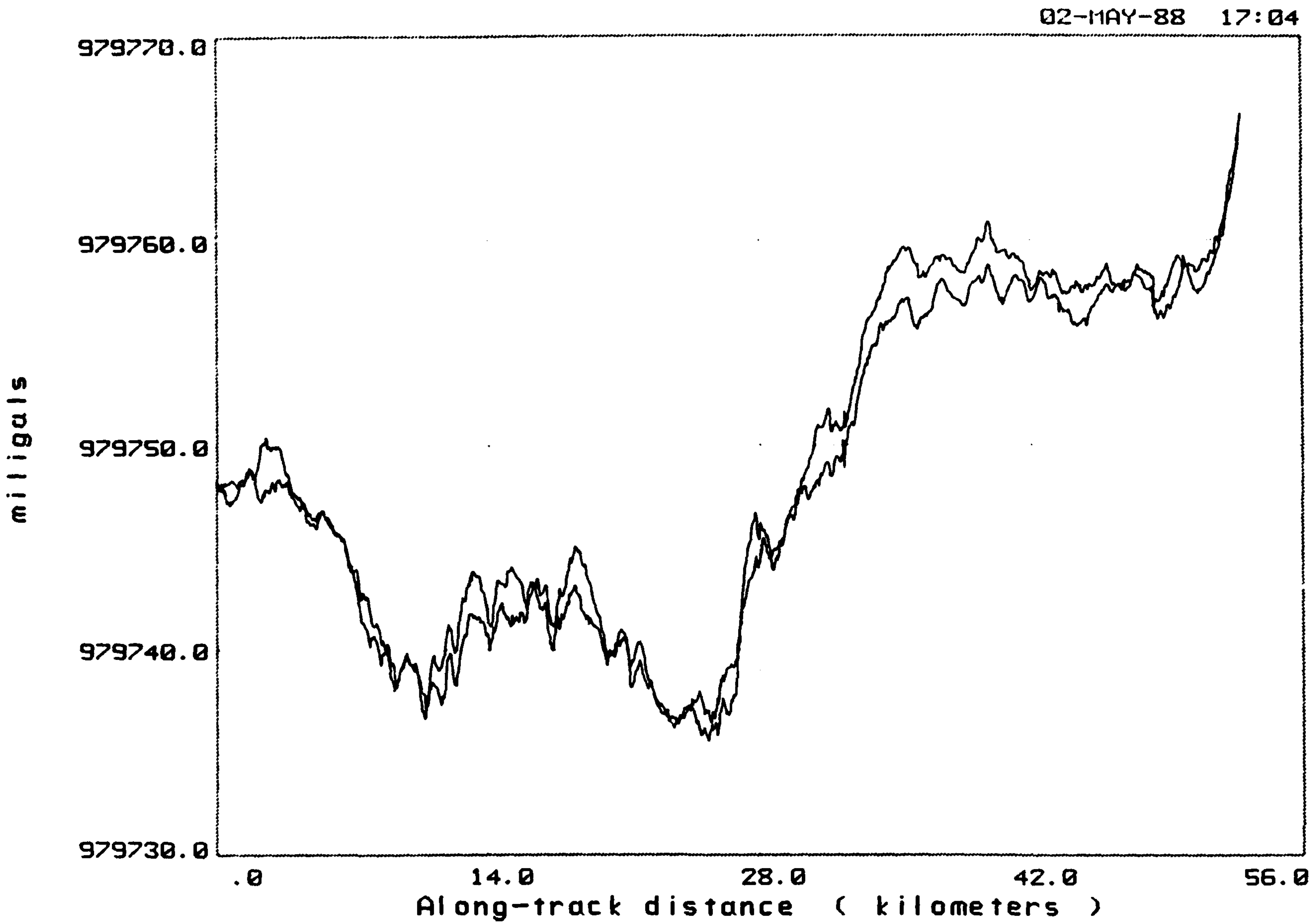
- After the phase II testing was completed, it was determined that system temperature control settings were improper with the result that binnacle temperature control was continually on the stop. Again a condition probably prevalent throughout the test.

- A number of the GPS related problems were troublesome;

    - GPS satelites close to the horizon gave erroneous ranges before the range information was classified as non usable. The false ranges caused platform control problems with long recovery times.

GRAVITY GRADIOMETER ground vehicle survey area





Oklahoma Land June 6,9 87 Repeats, TZ Disturbance

FIGURE 2-4A

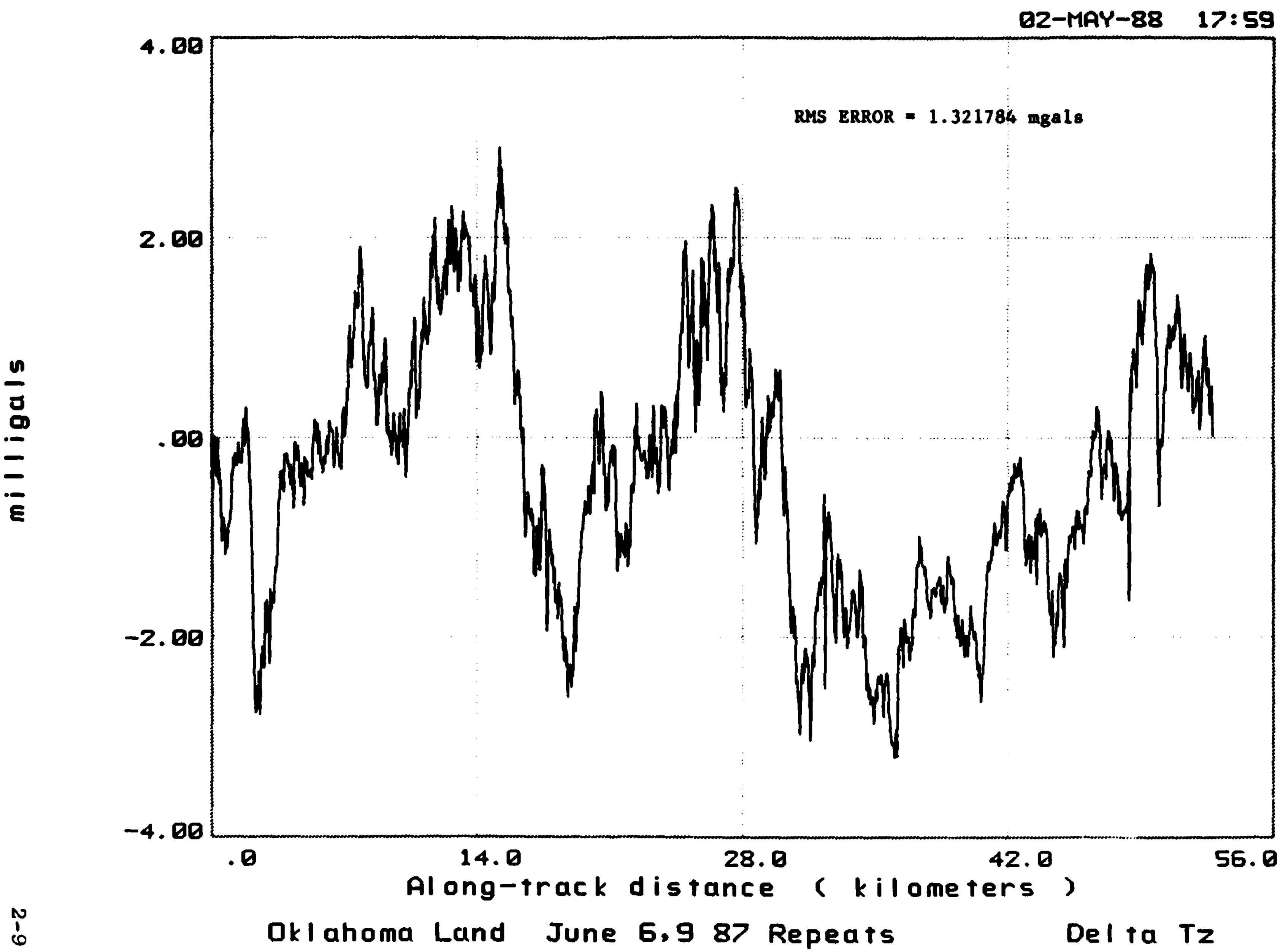

02-MAY-88 17:59
RMS ERROR = 1.321784 mgals
4.00
2.00
.00
-2.00
-4.00
milligals
.0
14.0
28.0
42.0
56.0
Along-track distance (kilometers)
Oklahoma Land June 6,9 87 Repeats
Delta Tz

FIGURE 2-4B

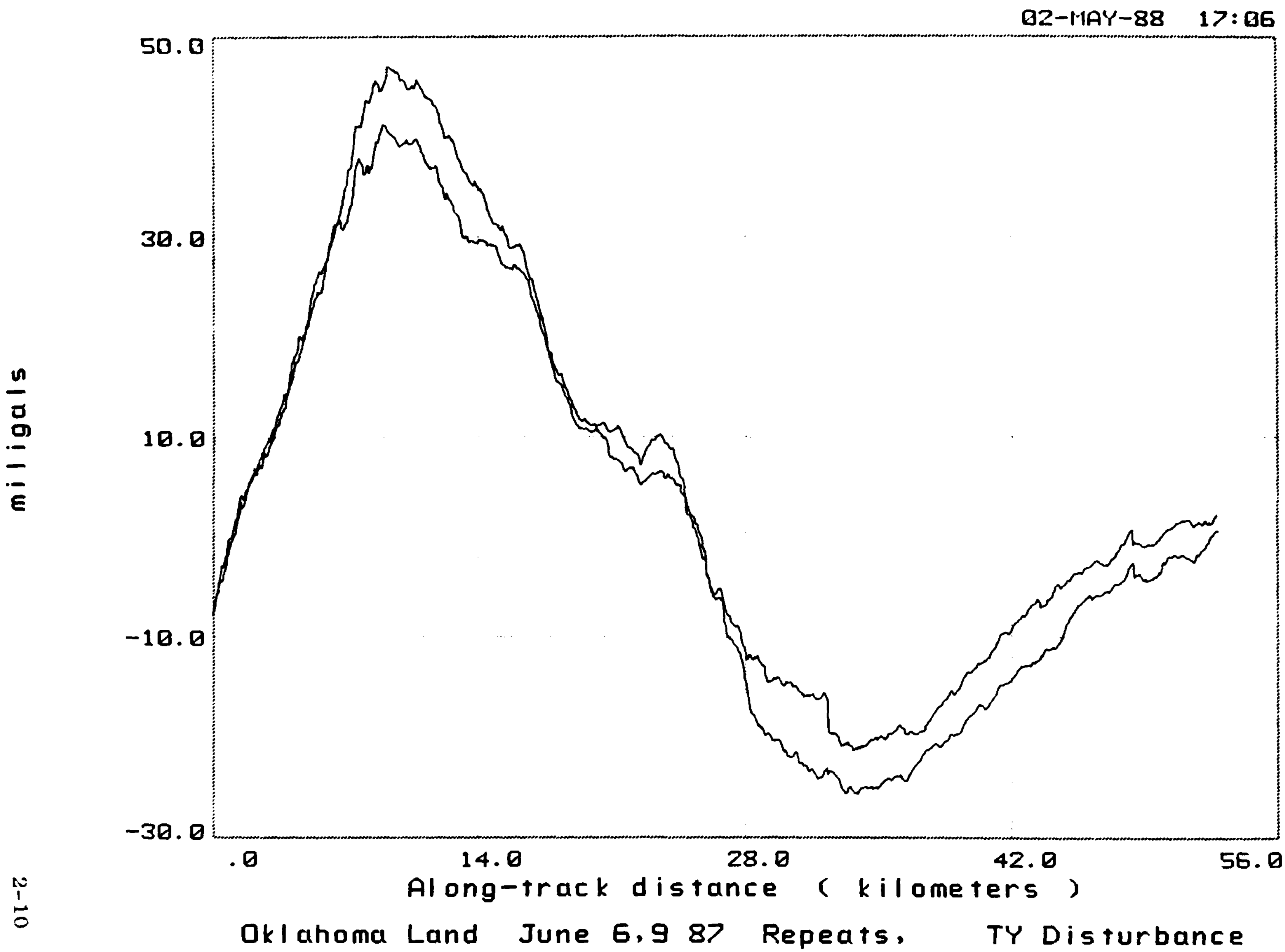

02-MAY-88 17:06
50.0
30.0
10.0
-10.0
-30.0
milligals
.0
14.0
28.0
42.0
56.0
Along-track distance (kilometers)
Oklahoma Land June 6,9 87 Repeats, TY Disturbance

FIGURE 2-5A

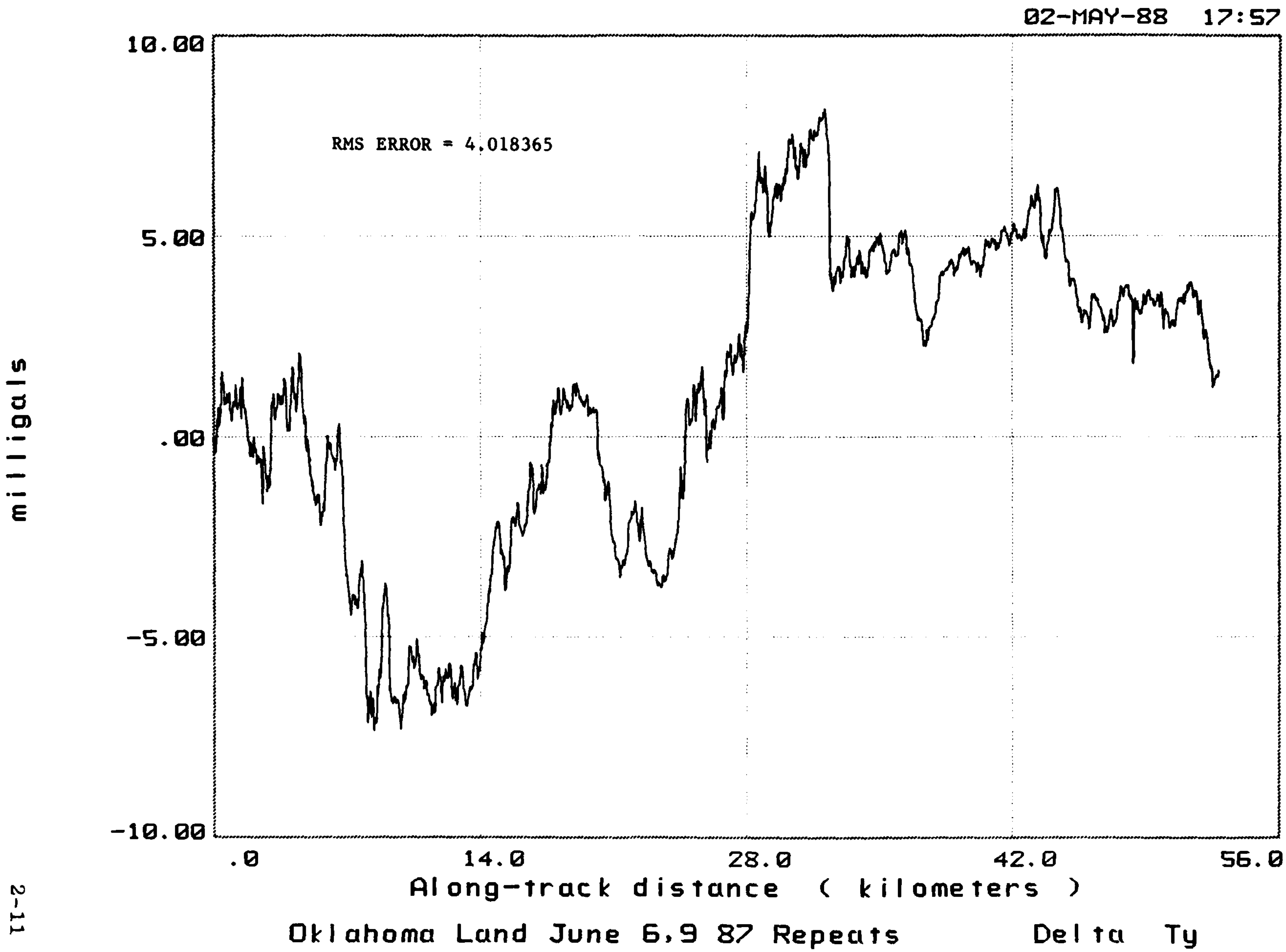
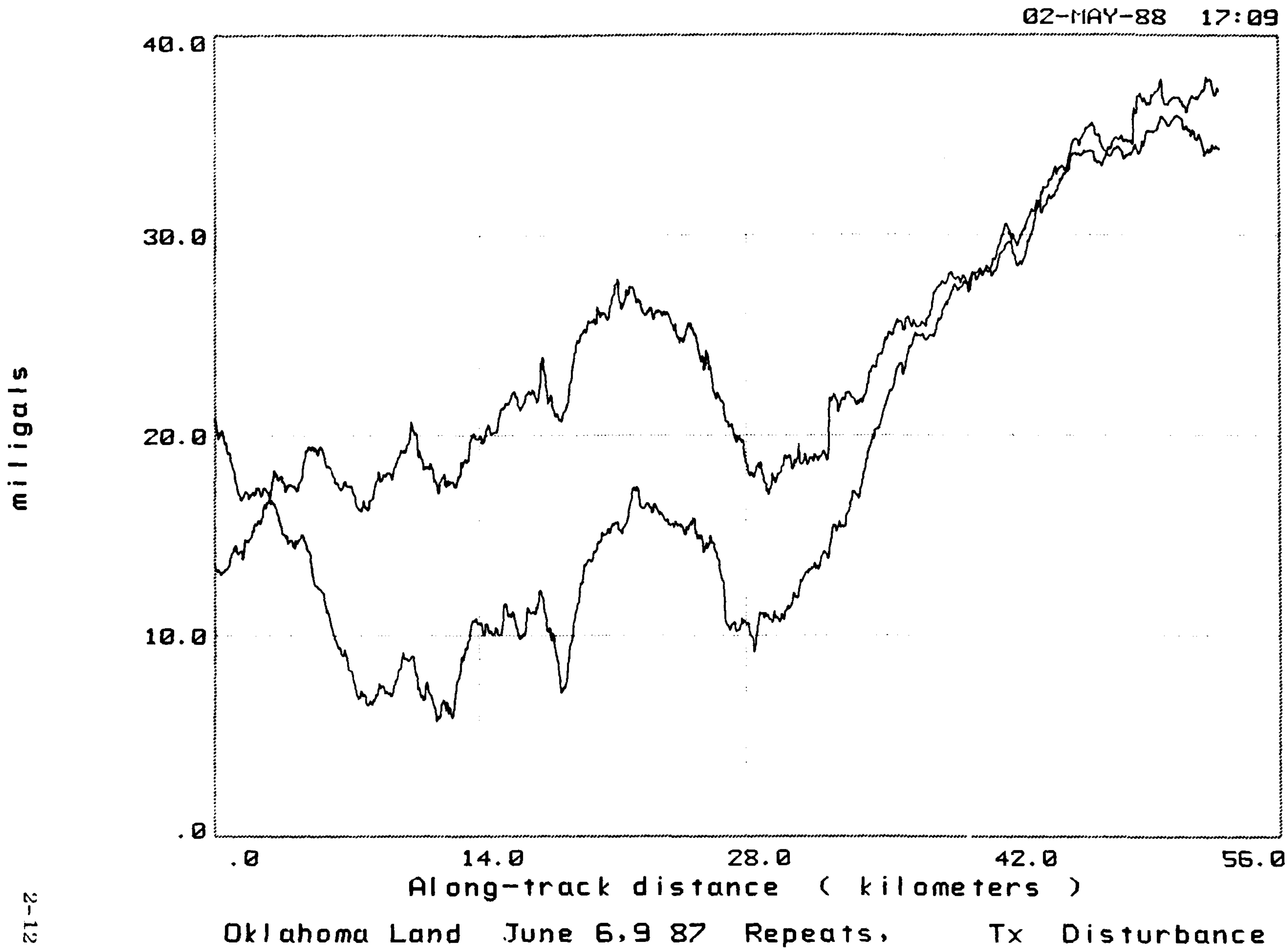

02-MAY-88 17:57
10.00
5.00
.00
-5.00
-10.00
milligals
RMS ERROR = 4.018365
.0
14.0
28.0
42.0
56.0
Along-track distance (kilometers)
Oklahoma Land June 6,9 87 Repeats Delta Ty

FIGURE 2-5B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30.0
20.0
10.0
.0
milligals
.0
14.0
28.0
42.0
56.0
Along-track distance (kilometers)
Oklahoma Land June 6,9 87 Repeats, Tx Disturbance

FIGURE 2-6A

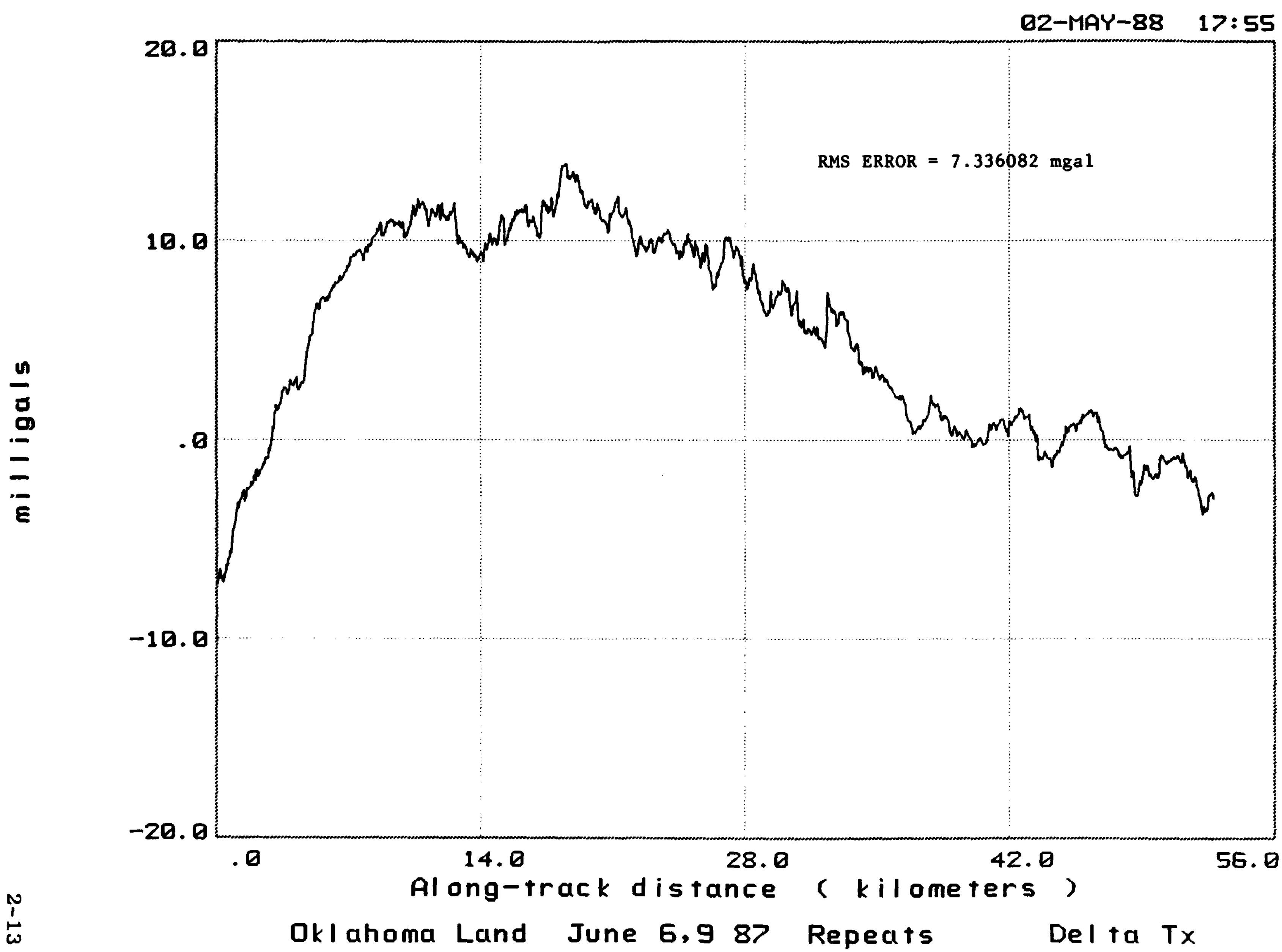

02-MAY-88 17:55
RMS ERROR = 7.336082 mgal
20.0
10.0
.0
-10.0
-20.0
milligals
.0
14.0
28.0
42.0
56.0
Along-track distance (kilometers)
Oklahoma Land June 6,9 87 Repeats Delta Tx

FIGURE 2-6B

- Satellite ephemeris data was bad or satellites were moved without notice.

- Sunspot activity (nuclear radiation) resulted in erroneous GPS signals or no valid signal at all.

- The GGI interface buffer had design errors. Most of these errors were recoverable in the post mission processing but some were not and some of these may have caused platform control problems.

- Filter micro processor (FMP) accelerometer outputs were not useable so post mission processing had to rely on acceleration sampled at a marginal 16/sec rate.

- Stage II data reduction was not geared to accommodate incomplete data.

- Aircraft self gradient data was taken with static platform attitude. Subsequent experience on the GSS program demonstrated much improved self gradient calibration by collecting data in the carousel mode.

- Probably the most troublesome finding is the clear evidence observed in the repeat track traverses, present in the land vehicle phase II testing, that GGI's are stepping at irregular intervals. Since this behavior has not been normally observed on shipboard operation, we can probably conclude that it is the harsher acceleration environment that is causing the steps. This phenomenon is being investigated further by repeat traverses at different speeds and correlation of these events with acceleration. In all likelihood these steps may have occurred with some frequency during the airborne testing in association with wind gusts or turns between tracks. These events were not observable in airborne data because of the lack of repeat track airborne data.

2.4 Recommendations

The GGSS test program was not a complete success, but it has demonstrated feasibility of airborne and land vehicle gradiometry. The potential benefits of this technology to geodesy, geophysics, and to the military warrant a continued high level of development effort. The test program has uncovered a number of areas requiring further development in hardware, software, and procedures. Much of this development is currently underway.

- Gradiometer bias stepping in the land vehicle is under investigation.

- Deficiencies in thermal control have been remedied.

- Test procedures for controlling gradiometer bias, including operation in a constant carousel mode, are being investigated.

More reliable and accurate self gradient calibration procedures have been developed.

- The complexity of the post mission processing problem requires more powerful computers to expedite turn around time of test and survey data.

The ongoing land vehicle test program is being used to demonstrate the efficacy of these refinements.

At this juncture consideration should be given to adding a gravimeter channel to the system and to begin flight testing of an integrated airborne Gradiometer/Gravimeter/GPS survey system. This system integration should be designed to fully exploit the synergies inherent in these systems. With this system our knowledge of the earth's gravity field in terms of global extent of coverage and in terms of a wide band of spatial frequencies could expand at a rapid rate and at minimal cost.

3.0 SYSTEM EQUIPMENT DESCRIPTION

3.1 Hardware

A complete description of the physical configuration of the GGSS equipment including van installation arrangement and aircraft interfacing is contained in Bell report number 6496-947008 "Configuration Item Product Fabrication Specification for Land-Based/Airborne Gravity Survey System", issued December 1986. GGSS installation into the van is shown in Figure 3-1; van positioning in the C-130 is shown in Figure 3-2.

3.2 On-Line Software

3.2.1 Introduction

This section summarizes the design structure and processing requirements of the on-line software used on the GGSS program. The detailed descriptions are contained in GGSS System Program Performance Specifications, Bell Report No. 6496-944002, June 1987. A listing of the program in Fortran IV has been provided to AFGL under CDRL Sequence No. 201.

The computer inputs are detailed in the Interface Design Specification Report No. 6496-944012, CDRL 130/IDS.

The computer outputs are also detailed in the Interface Design Specification.

An abstract of the Gravity Gradiometer Survey System computer program by major functions is shown in Figure 3-3. The interdependencies among the function are shown as well as the interface to peripheral equipments.

The program is task oriented and operates under a real time operating system. This is accomplished by the control functions which accept data inputs from the Global Positioning System or from a 5th wheel during land vehicle operations, X, Y, and Z accelerations from the accelerometer integrating accumulators, gravity gradiometer gradient data from the loop control microprocessors, instrument control data signals from the gradiometer electronics, and keyboard commands from the system operator. It allocates computer system resources necessary to perform the required computations and then transfers the gravity gradient information and status to the gradiometer electronics or peripheral equipment as required.

The software accomodates both land vehicle and aircraft installations. The land vehicle does not have vehicle control, fuel gauge inputs or pilot/autopilot input/outputs. The aircraft does not have a fifth wheel input.

The parameters (calibrations, bias, trend, scale factor, misalignments) of the GGI's and of the Gyros and accelerometers used to maintain known instrument cluster orientation are determined by calibration. The test procedure and sequences are on-line software functions as is the data logging during these calibration tests. The data reduction to determine the values of these parameters in accomplished by off-line programs.

The program interfaces with the operator through the keyboard/cathode ray tube display to obtain commands as well as issue system performance information and status reports. It also interfaces with peripherals such as magnetic tape and disk, for recording of data and information for later data reduction and analysis.

Performance monitoring is accomplished by the operator requesting display of any system variable for display on the strip chart recorders.

FIGURE 3-1

GGSS-Land Vehicle Installation

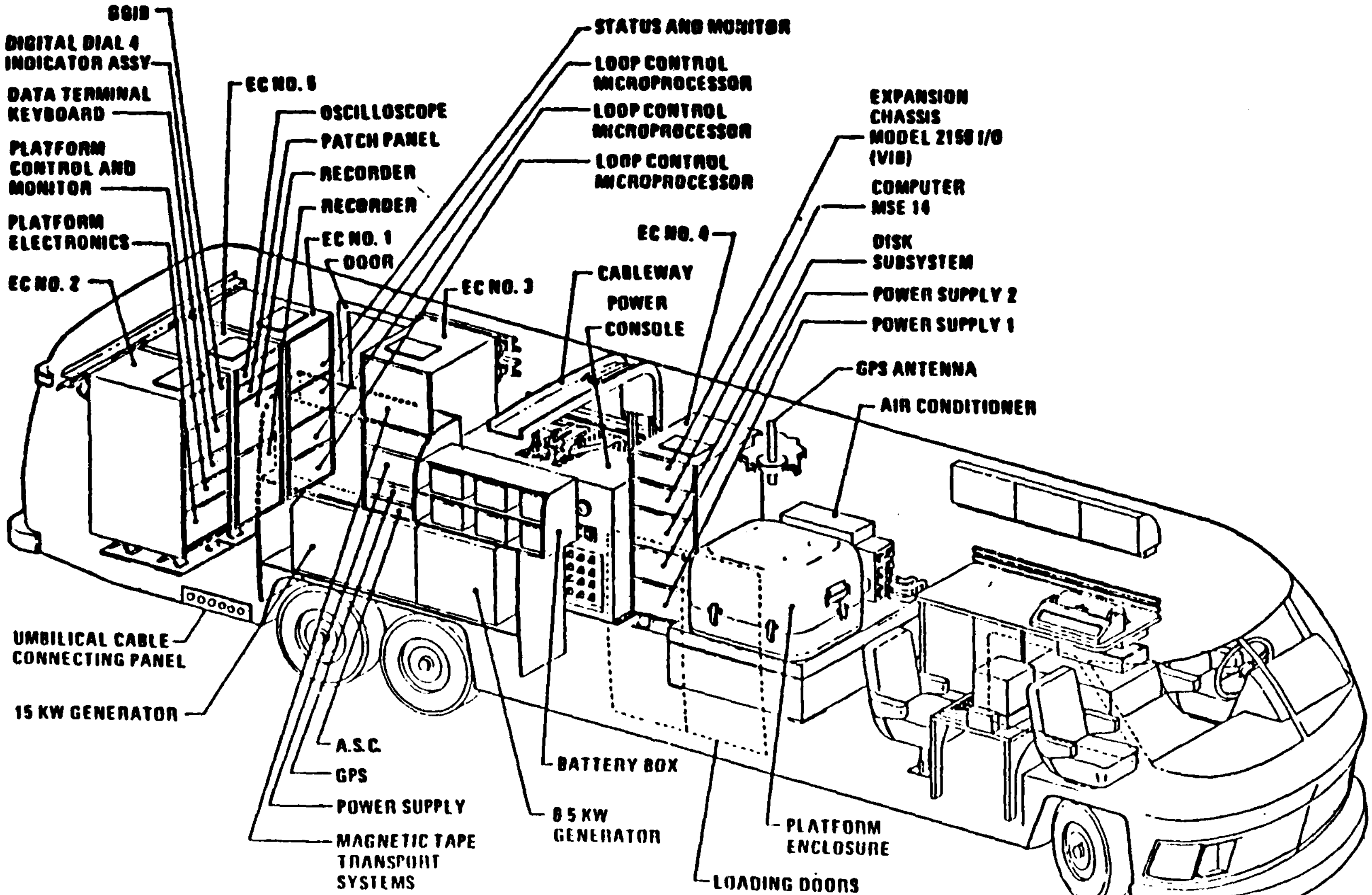
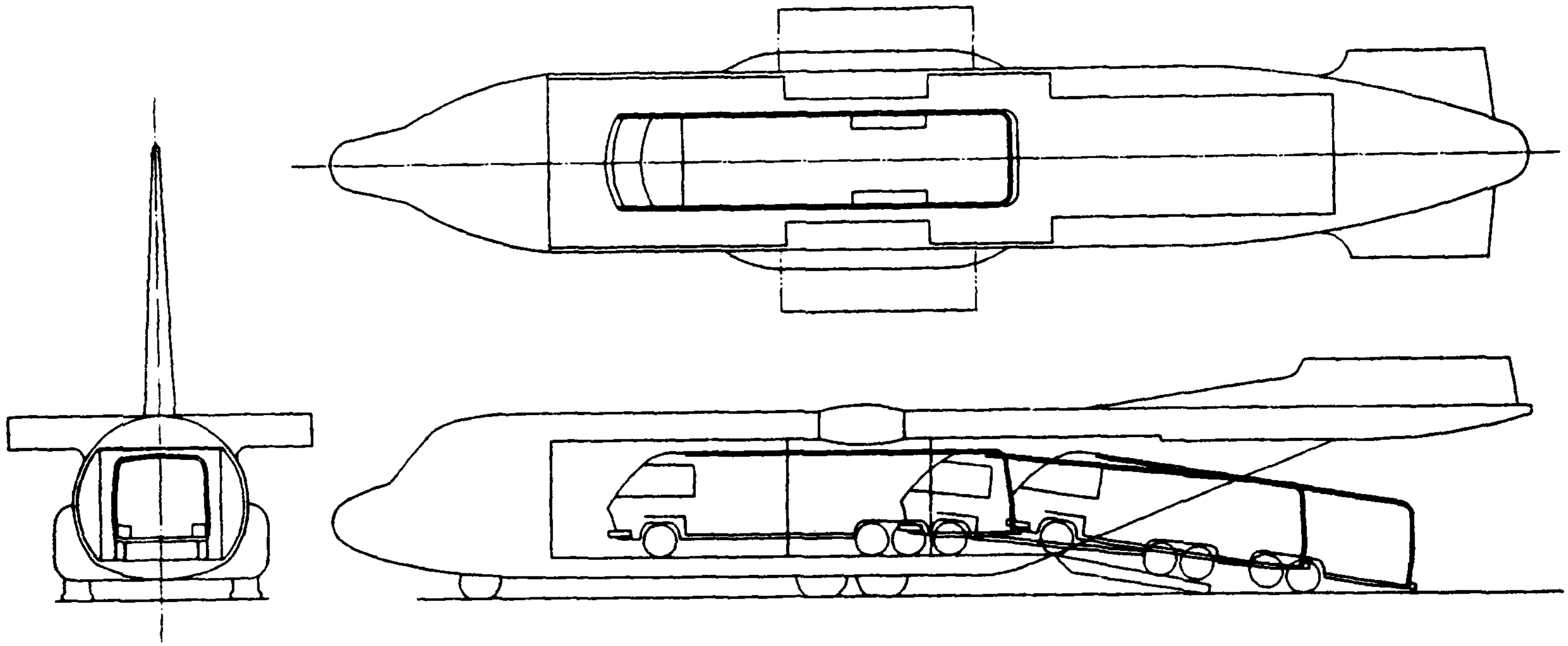


FIGURE 3-2

C130 INSTALLATION



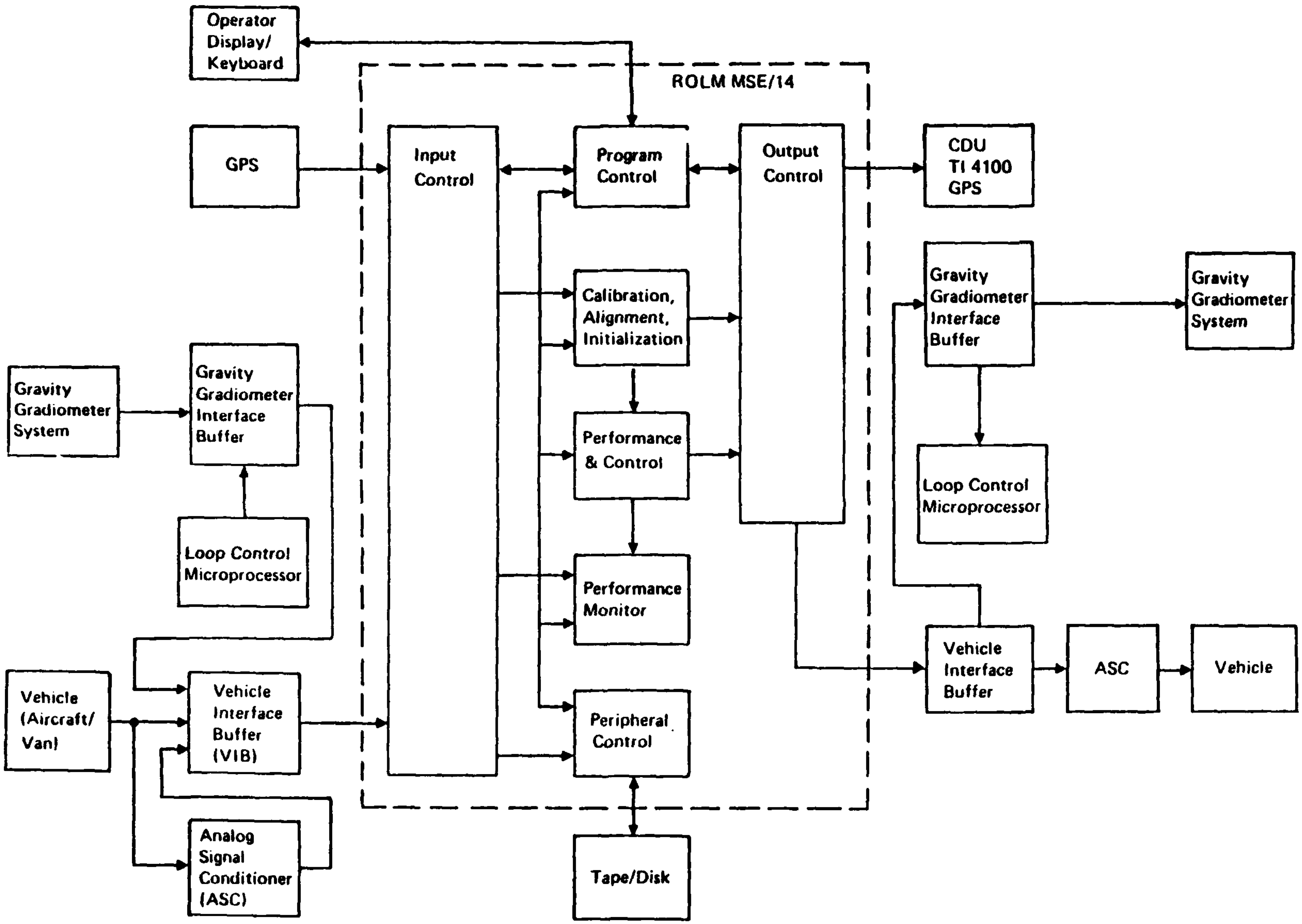


FIGURE 3-3 Gravity Gradiometer System Dedicated Operational Computer Program Abstract

3.2.2 Program Description

The on board Dedicated Operational Computer program is resident in the ROLM MSE/14 computing system. It receives navigation information from the GPS, or 5th wheel, gravity gradient data from the gravity gradiometer instruments, X, Y, and Z accelerations from the accelerometer integrating accumulators, and operator input commands through the keyboard unit. This data is processed to produce usable gravity gradient data which is recorded. Plotting and printing as required is performed off line.

For additional program performance information, refer to:

INTERFACE DESIGN SPECIFICATION
GGSS PROGRAM
REPORT 6496-944012
CDRL 130/IDS

SYN 6502 PROGRAM PERFORMANCE SPECIFICATION
GGSS PROGRAM
REPORT 6496-944304
CDRL 130/PPS1

T19900 PROGRAM PERFORMANCE SPECIFICATION
GGSS PROGRAM
REPORT 6496-944404
CDRL 130/PPS2

The Dedicated Operational Computer performs six major functions.

1. <u>Interface</u>

The computer program interfaces with all major Gravity Gradiometer Survey System elements - as shown in Figure 3-3.

Figure 3-4 is a function flow diagram of the equipment/computer relationship showing the data flow between the central computer and other system equipment.

The Program Control, and Operator Control function accepts control inputs entered by the operator to direct the accomplishment of the desired functions.

All computer inputs and outputs, except for peripherals (disk, terminal, magnetic tape, and keyboard), are controlled by the Input/Output Control process.

2. <u>Preparation</u>

The on-line software provides calibration, alignment, and initial platform level prior to mission start to orient and control the Gravity Gradiometer Survey System platform. On-line, real time processing corrects for instrument bias, misalignments, and scaling errors.

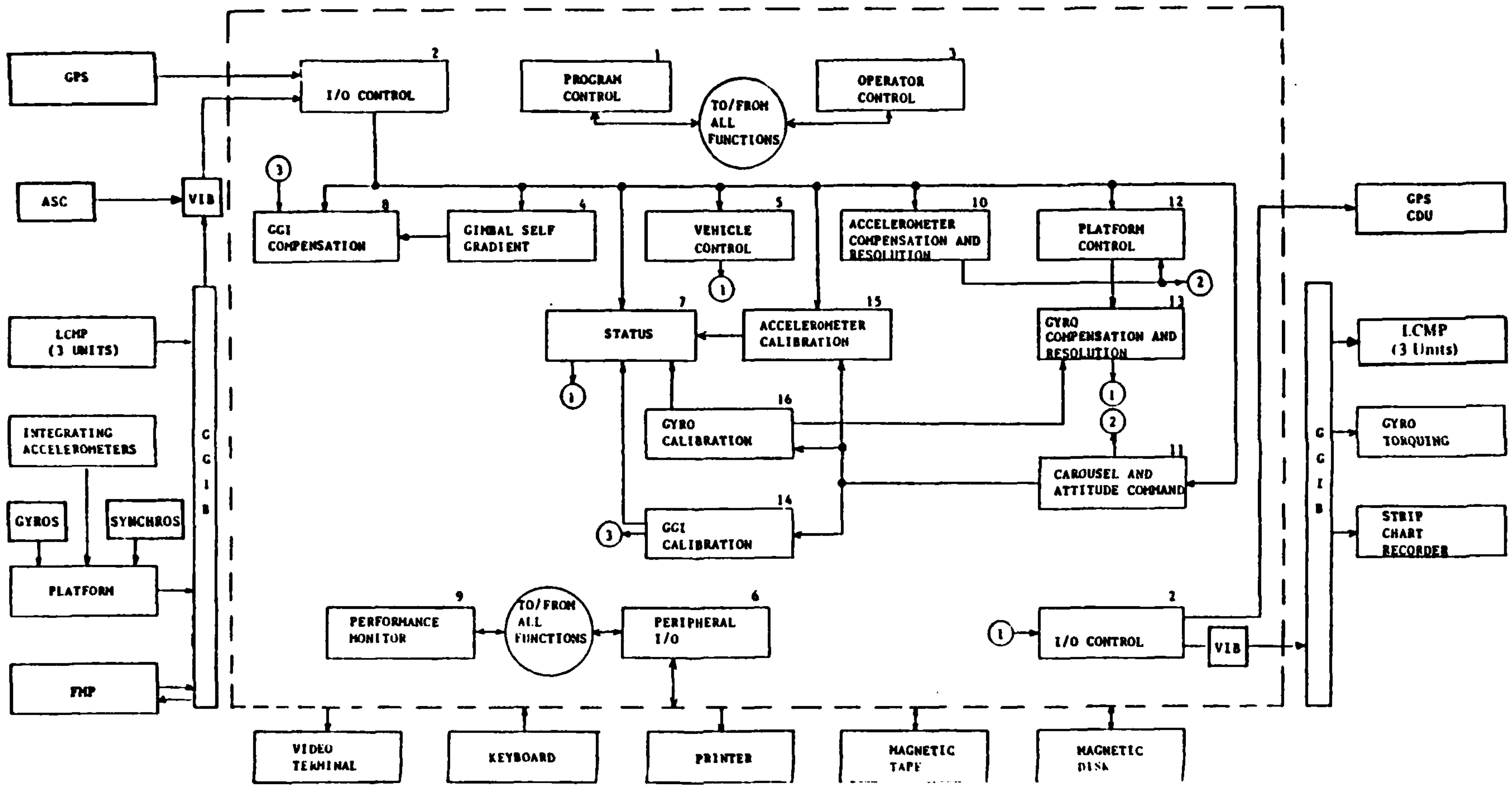


Figure 3-4

Functional Flow Diagram

The Gravity Gradiometer Instrument scale factor is determined in the laboratory and supplied with the instrument. This data is input to the computer program by the system operator. Capability for recalibration is provided. The software controls the platform in executing specific manuevers such as rocking the platform at known frequency and amplitude. Another specific test manuever is carouseling at predetermined rates. During these calibration manuevers the uncompensated gradiometer outputs are compared with the expected values from these motions and the instruments calibrated.

The software similarly executes additional specific manuevers to calibrate the accelerometers and gyros.

Gradients caused by the mass of elements located within the Gravity Gradiometer Survey System that move with respect to the gradiometer sensing elements are compensated for in the gradient output processing software.

Accelerometer calibration is required to determine the bias and scale factor of the platform accelerometers. The accelerometer signals which are used by the Platform Control function are corrected by these calibrations.

Gyro calibration is required to determine the bias and scale factor of the platform gyros. The gyro torquing signals which are transmitted to the platform gyros are corrected by these calibrations.

3. Platform Control

At power up, the platform is oriented and controlled to a fixed attitude. Thereafter, it is maintained and corrected when update signals are received.

There are two modes of platform control. The RUN MODE is the primary mode of operation. Leveling and alignment equations are implemented to compute platform position from velocity increment information measured by the X, Y, and Z accelerometers mounted on the platform. The computed position is then compared with the position data supplied from the navigation subsystem (GPS or 5th Wheel). The differences are the position error signals.

The secondary mode of Platform Control is accomplished by commanding the platform synchros to the desired attitudes. The differences between the attitude commands and the platform synchros are the attitude error signals.

Any error detected is used to generate correction torques to the platform gyros. The magnitude is computed by the control algorithms.

The on-line software computes the torquing signals in the Platform Control function and resolves them into the platform coordinate system and also corrects for gyro bias and scale factor of the electronics and misalignments in the platform installation.

Before the platform accelerometer signals A_x, A_y, and A_z, as received from the Input Control function, can be used by the Platform Control function, they are corrected for bias and scale factor and misalignments in the platform installation by the software in the Accelerometer Compensation and Resolution function.

The Carousel and Attitude Command function generates the attitude control matrix ([NP]). Platform attitudes are with respect to north/level in the RUN MODE and with respect to the vehicle axes in the CAGED MODE.

4. Peripheral Control

All raw input data from the Nav subsystem, the X, Y, and Z accelerometers, platform synchros and from the Gravity Gradiometer Instruments used by the computer are recorded on magnetic tape for later analysis. For the aircraft, the fuel states are also recorded.

All interfaces to the CRT, keyboard, magnetic tape, and magnetic disk peripherals are processed by the Peripheral I/O function.

5. Performance and Status Monitors

Operator selected variables are displayed on the strip chart recorder for rapid assessment of performance. This is the essential on-line performance monitor.

The Status function receives operator inputs from program mode control such as switching in of calibrate functions, as well as information from the gradiometer control. Status words are updated by the Status function.

6. Vehicle Control

(a) Aircraft

Flight pattern generations, autopilot commands, and position errors of the vehicle are computed and displayed to the pilot. The software processes GPS data to establish the immediate aircraft position.

Bank commands and altitude errors to hold track and altitude are outputted for autopilot (A/P) control. Manual or A/P control of the aircraft are selectable options.

(b) Land Vehicle

The software processes 5th Wheel data with the platforms attitude angles to provide a navigation references for land vehicle surveys.

The coordinates of known fixed points along the traverse are inserted by operator request to correct platform drifts.

3.3 Off Line Data Reduction Software

A number of offline software programs were developed to support the GGSS test program;

- Platform inertial component (gyros and accelerometers) calibrations.
- GGI scale factor and alignment calibration based on multirate carouselling tests.
- Self gradient calibration for both the land vehicle and aircraft.
- Computation of the terrain component of gravity field based on terrain elevation data.
- GGI linear and nonlinear acceleration sensitivity based on mission data.
- GGSS post mission processing consisting of stage I and state II processing for both the land and airborne survey data.

Description of the offline software is found in this report or in supporting documents which will be referenced.

4.0 System Integration, Pre-Survey Tests and Post-Survey Refurbishment

4.1 Introduction

The GGSS program was conducted in distinct phases. In chronological order, these were:

- Integration and laboratory tests
- Land vehicle installation
- Aircraft installation
- Aircraft tests
- Land vehicle tests
- Oklahoma airborne surveys
- Oklahoma land mobile surveys
- Post-survey refurbishment and test

The Oklahoma gravity surveys are treated in section 5.0 and 6.0 for the airborne and land surveys respectively. The laboratory tests and results are recorded in section 4.2. Section 4.2 follows the outline of section 2.0 of System Test Plan, Bell Report No. 6496-928004, May 1985.

The remainder of section 4.0 is organized under the major headings:

4.3 Land Vehicle Installation
4.4 Van Gradient Calibration
4.5 Aircraft Installation
4.6 Aircraft Gradient Calibration
4.7 Field Tests

Under the heading of Field Tests, the principal results are reported of the flight tests and road tests made prior to the Oklahoma surveys and the additional findings in road tests after the van was returned to Bell Aerospace. The field test results are not discussed in historical order. For clarity, the presentation discusses problems and solutions with references to their impact on each subsystem at each of these field test phases.

4.2 System Integration and Laboratory Tests

4.2.1 Introduction

This section describes the laboratory testing of the GGSS system in bay 5 of the Electronic Test Area at Bell Aerospace Textron, Wheatfield, New York, These tests were performed between 1-28-86 and 8-30-86.

The AFGL GGSS consists of eight major subsystems:

- Global Positioning System (T14100)
- Platfrom and INS Environmental Conditioning System
- Three Gravity Gradiometer Instruments (GGI)
- Three Electronic Racks
- Data Processing and Data Logging System
- The Host Vehicles (Land and Aircraft)
- Peripheral Equipment

All these subsystems, except the host vehicles and Aircraft Signal Conditioner (ASC), were assembled and interconnected in Bay-5. The host vehicles were simulated in so far as spatially pointing the platform system were concerned by mounting the platform on a 2-degree of angular motion table. The platform systems are protected by a shroud. The shroud's interior is temperature and humidity controlled by internal air conditioning. The air conditioning system in Bay 5 provided the environmental control for the GGSS Electronic Racks and the ROLM MSE/14 computer.

The shroud, platform and inertial instruments were mounted by their isolation system to a two axis angular test table (commonly referred to as Scorsby table) model S-546B Careo Electronics, Menlo Park, CA.

Figure 4-1 shows the Laboratory Test Assembly in Bay 5. This figure shows the platform assembly with the upper half of the shroud removed. The platform assembly sits within the lower half of the shroud which is mounted on the CARCO Scorsby Table. The racks at the right side of this figure, from the furthest to nearest, contain the computer tape drive and GPS, the platform control electronics, the GGI electronics and the strip chart recorders. The ROLM computer is not seen, being behind the camera in this view.

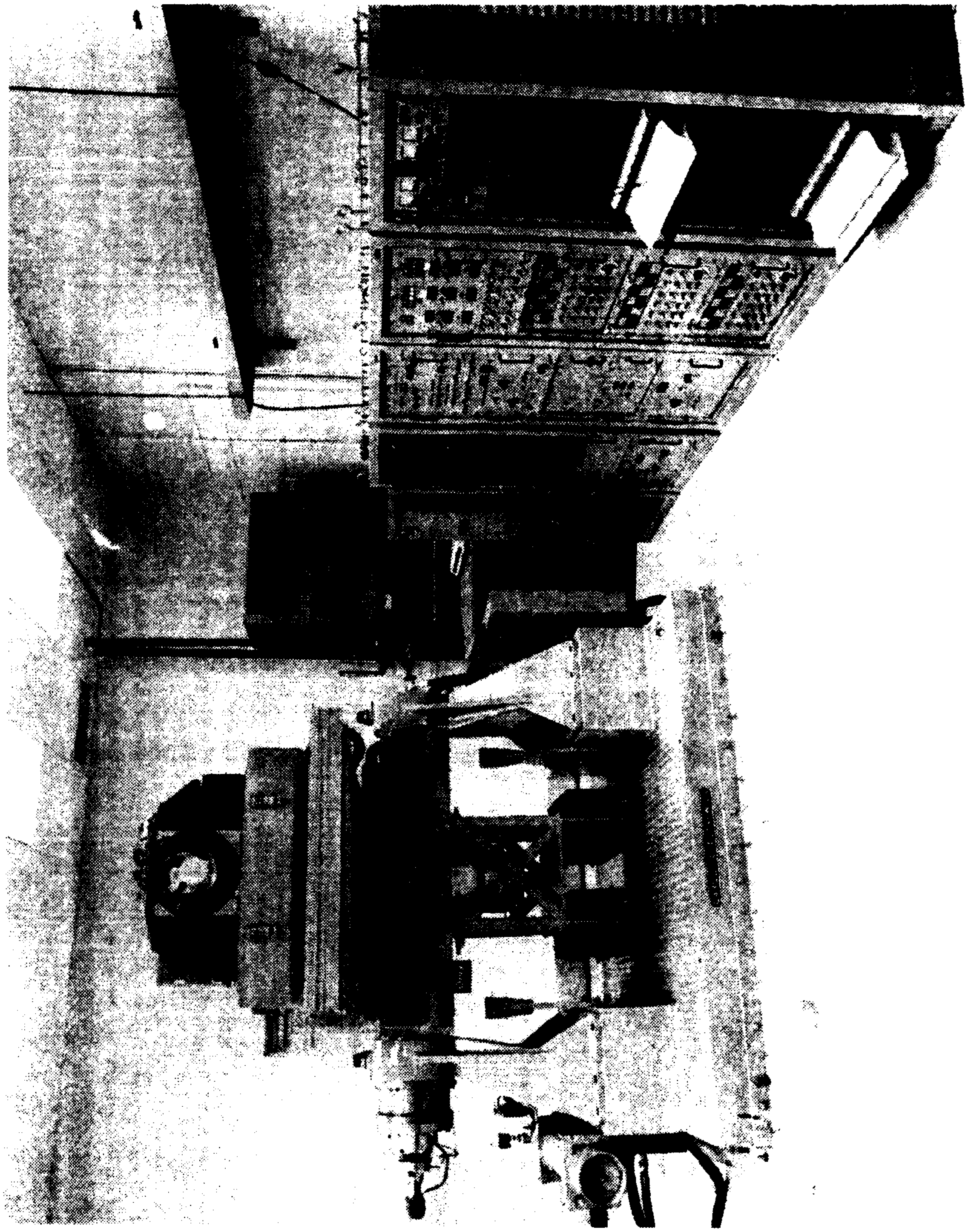
A roof mounted L-band antenna and co-axial cable from the roof to Bay 5 were used to bring GPS satellite signals to the T1-4100 Navstar receiver.

The test order was determined by dependencies. Tests calibrations and evaluations which required performance of earlier tests were positioned behind the required predecessor tests. The tests were performed in the following sequence.

- Operational Mode, Caged Platform
- Inertial Instrument Calibration (LAA and Gyros)
- Operational Mode, Navigating Platform
- GGI Calibration
- System Noise Performance, Static
- Self-Gradient Determination
- System Noise Performance, Dynamic

Figure 4-1

Laboratory Test Assembly



The Reliability/Maintainability Demonstration was integral with all the laboratory tests. The Reliability/Maintainability experience during laboratory tests was the data used for the demonstration. The demonstration results are reported separately under CDRL 108. The GGSS Reliability/Maintainability Demonstration plan requires a minimum of 1000 hours. The actual number of hours logged was 5800 hours.

The general controlling document was System test plan, Bell report no. 6469-928004 Rev. D, Nov. 1985.

The equipments required to execute this plan were:

1. Equipment List/Facilities

   - Two Axis (CARCO) Table
   - AFGL/GGSS Platform Enclosure Mounted to Scorsby Table
   - AFGL/GGSS Racks
   - ROLM MSE/14 Computer
   - T1 4100 Navstar Receiver/Processor with roof mounted antenna.
   - Bell Standard laboratory multimeters, oscilloscopes, and recorders. These will be specifically identified with the test data package for each test.

2. Special Equipment Description

   Carco Model S-546B Scorsby Table

   The platform, its isolation system and the enclosing shroud with its air conditioner were mounted on the Scorsby table. The Scorsby tables outer or roll axis is parallel to the horizontal plane and surveyed in to be parallel with a true East-West line. The survey errors have a maximum possible misalignments of 1.8 arcminutes in the parallelism of the roll axis with true East-West. The roll axis is the reference for platform headings in azimuth. The gyrocompassing erros in platform alignment are permitted to be 17 minutes RMS so a maximum reference error of 1.8 arcminutes is acceptable. The inner (azimuth) axis of the Scorsby is perpendicular to the roll axis to within 30 arc seconds maximum based on manufacturers specifications.

3. Power Requirements: GGSS

   - 60 Hz, Phase, 115 VRMS, 3575 W
   - 400 Hz, 1 Phase, 115 VRMS, 2720 W

4. Power Requirements: Scorsby

   - 50 Hz, 440 VAC. 20 A

5. Maintenance of Calibration of Test Equipment

Calibration was maintained in accordance with Bell Metrology directives MD-1 through MD-26.

6. Environment

Existing laboratory, white room environment.

7. Items to be Tested

The GGSS platform and GGIs were tested using the ROLM computer and TI4100 Navstar GPS in conjunction with Carco Model S-546B Scorsby table.

8. Test Description

Position coordinates were provided by the TI4100 GPS for RUN mode tests. The operator keyboard provided commands for the CAGED (synchro control) mode. Calibration modes were tested with command generated by the calibration subroutines. All lab tests were performed with the platform mounted to the Scorsby table.

9. Verification Prior to Start of Test

The system was operated for at least 2 hours prior to start of tests.

10. Each test was conducted in the presence of, and under the supervision of, an assigned engineer.

4.2.2 Operational Mode, Caged Platform

A. Preliminary Synchro Null Offset (SNO) Calibration

Subsequent tests required reading the platforms synchros for platfrom position information. To calibrate the synchros with respect to the reference system, the synchro readings (offsets) when the platform was aligned with the axes of this reference system were measured.

The pitch and roll SNO's were the synchro output values required to erect the platform azimuth bearing axis to vertical when the platform frame was leveled (i.e., when the machined top edge of the frame was level.)

The azimuth SNO was the synchro output value which aligned the "X" accelerometer axis of the DAA parallel to the platform pitch axis.

The inner element optical cube (IEOC) was mounted and aligned for use as a procedural aid to find the synchro SNO's. No subsequent use of the IEOC during lab or vehicle testing was required.

The Synchro Null Offsets measured for the AFGL platform were as follows:

Pitch SNO	=	0.05°
Roll SNO	=	0.25°
Azimuth SNO	=	359.95°

B. Caged Platform Test Procedure and Requirements

1. The primary purpose of this test was to determine that the pitch, roll, and azimuth gimbal angles assume the attitudes commanded by the operator or by the test subroutines. The secondary purpose was to determine that the synchro loop responses are within design specification.

   The synchro system is organized such that, when the vehicle headings, Ψ_{pv}, is entered (operator entry) into the attitude command matrices, the synchros read the platform attitude with respect to a North-East-Down (NED) coordinate system. This provides a means for orienting platform components such as the gyros with respect to the geographic system for calibration purposes. Since the orientation of the Scorsby Table was equivalent to a ship going East, Ψ_{pv} was entered as 90° and azimuth synchro reading, Ψ_{sy}, was related to the azimuth synchros command by $\Psi sy = 90^\circ + \Psi c$.

3. The operator entered the commands as shown in Table 4-1 and after platform settling recorded the ROLM and EC #2 synchro display readings.

4. The pitch, roll, and azimuth synchro readings read in the ROLM software were brought out through ROLM D/A control to the strip chart recorder. As read on on the strip charts, the time (T) to reach first overshoot maximum on each of the three axes after each command change were not to exceed 150 seconds and the overshoot (A) to not exceed 20% of the commanded change (see Figure 4-2).

C. Caged Platfrom Mode Results

Table 4-1 lists the ROLM synchros and EC #2 panel synchros (coarse check) readings obtained. Table 4-2 summarizes these results and also shows observed worst case vales of T and A (see B.4 above). These were so far within specification that the values for each synchro command setting were not individually recorded.

Table 4-1. Synchro Commands and Readings

Run Number	Synchro Commands PI, RO, AZ	Gimbal Readings PI	RO	AZ	Panel Readings AZ	PI	RO
1	0, 0, 0	.04944	.2472	89.95189	90.1	0.1	0.1
2	10, 0, 0	.04944	10.2504	89.95189	90.1	359.9	10.0
3	10, 0, 90	350.0515	.2472	179.9478	179.9	350.1	0.1
4	10, 0, 180	.04944	350.2493	269.9546	270.1	0.1	350.4
5	10, 0, 270	10.05264	.2472	359.9504	0.0	10.0	0.2
6	0, 10, 0	10.05264	.2472	89.94643	90.1	10.1	0.1
7	0, 10, 90	.04944	10.2504	179.9478	179.9	359.9	10.0
8	0, 10, 180	350.0461	.25269	269.9436	270.0	350.2	0.1
9	0, 10, 270	.04944	350.2493	359.9504	0.1	0.1	350.4
10	0, 90, 0	90.05078	.25269	89.95189	90.1	90.	0.1
11	-90, 0, 90	90.05624	.25269	179.9478	179.7	90.0	0.2

NOTES:

1. All readings are in degrees
2. Az = Azimuth
   PI = Pitch
   RO = Roll

Figure 4-2. Response Definitions

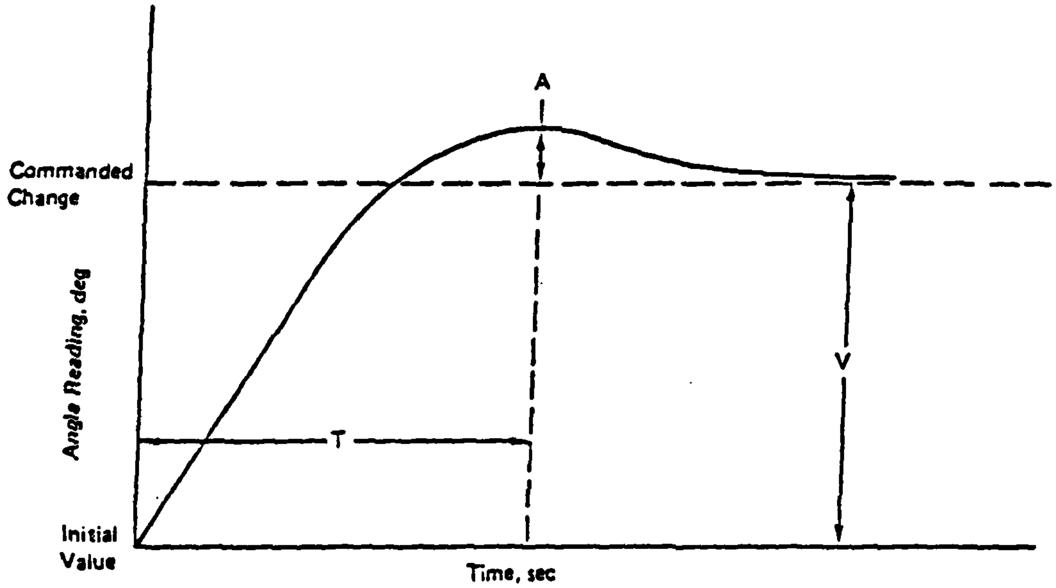


Table 4-2

SYNCHRO CAGE TEST RESULTS
(11 ATTITUDES)

LARGEST ERRORS: PITCH .0039° = 14 ARC SEC
ROLL .0028° = 10 ARC SEC } SPEC 20 ARC SEC
YAW .0046° = 17 ARC SEC

CAGED LOOP STEP RESPONSES

(a) MAXIMUM TIME TO 1ST OVERSHOOT <30 SEC

(b) MAXIMUM OVERSHOOT <2° FOR 90° COMMAND CHANGE
SPEC: 20% OF COMMAND

4.2.3 Inertial Instrument Calibration (DDA and Gyro)

4.2.3.1 Platform Digital Accelerometer Assembly (DAA)

The purpose of this test was to calibrate the accelerometer triad (DAA) used to level the platform. The test was performed by calling the ACCEL CAL test subroutine in the ROLM MSE/14 program. The platform was operated in the CAGED mode with the ACCEL CAL test subroutine sequentially and automatically commanding specific attitude angles. The mean values of the accelerometer output at each of the platform test attitudes was recorded and the calibration parameters (bias, scale factor, and misalignment) of the accelerometer were computed by the firmware from these output. Table 4-3 shows the tolerances. The calibration parameters were used to verify the DAA functioning by comparing these numbers to expected values and checking for agreement to within specificied tolerances. The calibration parameters are used to compensate the accelerometer outputs for use in the Navigation Platform mode.

Reference documents generated on other programs which supported the test are: ADM GSS No. 2 In-House Evaluation Plan; Submittal No. 1 GSS Mode Test Plan (DEV-420 and DEV-430), Report No. 6501-928001, DDI D-40A, November 15, 1978.

A. Prerequisited Calibration/Adjustments

The CAGED mode of platform control was completed prior to DAA calibration. DAA calibration requires precise pointing of the platform with the respect to the gravity vector for calibration. This precise pointing is accomplished by synchro control in the caged mode which requires a calibrated CAGED mode.

B. Test Procedure

1. The Scorsby was set to 0° in heading and roll. The vehicle attitude angles in the synchro control matrices were set to zero. This initialization insured that the synchro commands in the CAGE mode were with respect to NED coordinates.

2. The ACCEL CAL subroutine was used. This placed the platform in the CAGED mode, and sequenced the platform to the required attitudes.

   The DAA calibration subroutine holds each platform attitude for a 10 minute stabilization period, followed by a 15 minute data acquisition period during which the accelerometer readings are averaged.

   The platform attitudes and the nominal averages of the three accelerometers (Ax, Ay, Az) are show in Table 4-3. In this table g is the laboratory value of gravity acceleration (9.8037 M/S^2).

C. Accelerometer Calibration Results

Subroutine ACCEL CAL combined the averages read and computed biases, scale factors and misalignment angles. The results are shown in Table 4-4 along with the specification values. In the table, the increments to the manafacturers biases as computed by the calibration algorithms are shown. These are ΔBx, ΔBy, ΔBz. The scale factor corrections are shown as multipliers to be applied to the manfacturers scale factor. These are Sx, Sy, Sz.

Table 4-3. Accelerometer Calibration Attitudes and Nominal Acclerometer Readings

		NOMINAL VALUES		
PLATFORM PITCH (degrees)	PLATFORM AZIMUTH (degrees)	Ax	Ay	Az
0	0	0	0	+gL
0	90	0	0	+gL
0	180	0	0	+gL
0	270	0	0	+gL
-90	0	-gL	0	0
-90	90	0	-gL	0
-90	180	+gL	0	0
-90	270	0	+gL	0
-180	0	0	0	-gL

Table 4-4 Accelerometer Cal Results

1. Acclerometers initialized with MNFR Bias & Scale Factors
2. Incremental corrections computed by CAL Algorithms
3. Summary of increments

MEASURED	SPEC
ΔB_x = 8.5 ug	3 mg
ΔB_y = 178 ug	
ΔB_z = 73 ug	
S_x = 1.000033	.9995-1.0005
S_y = 1.000266	
S_z = 0.99974	
LARGEST MISALIGN ANGLE 0.0019 RADS	±0.05

4.2.3.2 Gyros

The purpose of this test was to calibrate the platform leveling and heading gyros. The test was first performed by calling the Gyro Cal test subroutine in the ROLM MSE/14 program. This test subroutine was similar to that used for DAA calibration. Its essential features were:

1. Position the platform at key attitudes with respect to the earth's rotation vector.
2. Dwell at each position for 10 minutes and then average the torque signals to each gyro for 15 minutes.
3. Derive the biases, scale factors and misalignment angles of the gyros. The vertial gyro is torqued for platform North and East axes leveling and X-Y Gyro parameters are obtained. The horizontal gyro is torqued for platform alignment and Z Gyro parameters are obtained. The algorithms used are based on measuring the average torqued required by each gyro to maintain the platform stationary with known earth's rate components along the sensitive axes of the gyros.

Unlike the successful accelerometer calibration subroutine, subroutine GYRO CAL did not give correct answers. The symptoms were:

1. Estimates of misalignment angles which indicated orthogonality errors of several degrees between the gyros axes. The manufacturers specification state that these should not exceed 100 arc seconds.
2. Results appeared to indicate that the Gyros were heading sensitive.
3. Excess errors in gyrocompassing when the estimated biases were used. The principal reason for the failure of the algorithms were:

   The algorithrms assumed that the gyro biases were constant. In particular the biases were assumed to be the same for the gyro with its spin axis vertical or horizontal. This is known to be incorrect. The specification of the manufacturer, the Guidance and Control Division of Litton Industries allows the G1200 gyro to have a "G" sensitive drift of up to 5°/hr/g.

   The procedure was revised to calibrate the gyro in the positions in which they would be principally used namely, the X-axis of the vertical gyro pointing towards north and the Y-axis pointing east and with the Y-axis of the horizontal gyro pointing down. The latter is the platforms azimuth axis. The revised procedure is described in E. below.

A. Prerequisite Calibration/Adjustments

The Calibrations of sections 4.2.2 and 4.2.3.1 were completed. The revised gyro calibration procedure required accelerometer leveling and synchro control.

B. Acceptance Criteria

The acceptance criteria were simplified based on analysis of the requirements when the platform is under the control of a reference source such as GPS. With external references all parameters are compensated except the east axis bias. Errors in east axis bias are manifested by errors in the platforms north alignment. The acceptance criteria then was reduced to simply requiring that the north alginment error be less than 17 arcmin in Standard Deviation. This value is dictated by the gradiometer alignment required to meet system perfomance requirements.

C. Test Procedure for Directional Sensitivity

It was considered essential to establish that the gyros were not heading sensitive with respect to masses, electric fields, air flow and temperature gradients within the shroud. The procedure:

1. The platform was controlled in RUN MODE E. In this mode, the accelerometers level the platform as they would in the navigation modes. The platform's heading is controlled by synchro as in the CAGE MODE.
2. The Scorsby table was indexed in 30° steps for 360°. Using synchro control of azimuth, the platform was repositioned so that its x-axis always pointed north. This meant that the platform was stationary in space and in its normal operational attitude with respect to geogrophical coordinates. (The platform is defined as the inner element which carries the intertial instruments). The shroud, gimbals, torquers and all off platform structures then rotated 360° around the spatially fixed platform.
3. After each 30° index step, the total torque to each gyro was averaged for 2 minutes.
4. Since the earth's rate components seen by each gyro was a constant, any variations between index positions in the torque required by the gyros to hold the platform stationary would be due to gyro sensitivities with respect to the off-platform components. In flight or van travel, these components would move similarly with respect to the north & level seeking platform. This variation is termed Directional Sensitivity.

D. Directional Sensitivity Results

It was conclued that directional sensitivity was not significant and could be ignored. Table 4-5 lists the 2 minute torque averages obtained for each Scorsby heading and for each gyro. The variations noted as measured by the standard deviation was judged consistant with the limited number of samples in the two minute averages. This was shown by repeating a two minute average at the same index point. The variation between successive two minute averages taken without changing the platform or Scorsby positions have standard deviations of the same value as that obtained between different index points.

E. Test Procedure for Gyro Calibration

The revised gyro calibration procedures were:

1. The platform was first controlled in RUN MODE E. In this mode, the accelerometers level the platform as they do in actual naviagation. The platform heading is controlled by synchro as in the CAGE MODE.
2. The platform was indexed so that it successively pointed north, south, east and west (N,S,E,W). After settling at each index position, the total torque to each gyro was averaged for five minues. Define the torques as Ti j where i is the platform pointing direction and j is the gyro sensitive axis.

   i = N, S, E, W
   j = X, Y, Z

Table 4-5. Gyro Torques: Platform Fixed/Scorsby Indexed

SCORSBY HEADING (DEG)	GYRO TORQUES (DEG/HR)		
	X	Y	Z
0	-13.82	-1.81	-10.67
30	-13.82	-1.82	-10.69
60	-13.85	-1.81	-10.67
90	-13.84	-1.81	-10.64
120	-13.85	-1.82	-10.66
150	-13.82	-1.80	-10.68
180	-13.83	-1.83	-10.66
210	-13.81	-1.78	-10.66
240	-13.79	-1.81	-10.70
270	-13.82	-1.80	-10.67
300	-13.83	-1.80	-10.70
330	-13.84	-1.79	-10.64
AVERAGE	-13.827	-1.807	-10.67-
STANDARD DEVIATION	.017	.013	.019

3. The estimates of the X and Y gyro scale factors were obtained as follows where ΩH is the horizontal component of earth's rate.

$$Sx2 = \left(\frac{Txs - Txn}{2\Omega_H}\right) Sx1$$

$$Sy2 = \left(\frac{Tye - Tyw}{2\Omega_H}\right) Sy1$$

Sx2, Sy2 are new X, Y gyro scale factors and Sx1, Sy1 are their previous values.

4. The incremental X and Y gyro biases were obtained as follows:

$\Delta Bx = \frac{1}{4}$ (TXN + TXS + TXE + TXW)

$\Delta By = \frac{1}{4}$ (TYN + TYS + TYE + TYW)

The corrected biases = old biases + corresponding ΔB.

5. The platform was placed in the CAGED mode. In this mode all axes are synchro controlled. The platform was leveled and aligned using synchro control. The Scorsby was then rotated to align the platform roll axis to north.

6. The platform was then pitched up 90°. The torque to the Z-axis gyro was averaged for 5 minutes after the platform had settled in this orientation. Define this average as TZU.

7. The plaftorm was then pitched down 90°. After settling, the torque to the z-axes gyro was averaged for 5 minutes. Define this as TZD.

8. The Z gyro scale factor was obtained by

$$Sz2 = \left(\frac{TzU - TzD}{2\Omega H}\right) Sz1$$

The corrected bias = old bias + ΔBz.

10. The Scorsby was returned to its normal position which simulated a vehicle heading due east. The platform was put in RUN MODE B. In this mode, the platform is leveled by the accelermoters and aligned by gyrocompassing.

11. When the platform heading had stabilized under gyrocompassing, the Azmimuth synchro was read. With the Scorsby heading east, the platform synchro should read 90° for a simulated vehicle heading east. Call the reading $\Psi 0$.

12. The Y-gyro (East axis gyro) was fine trimmed by adding an additional incremental bias correction. The increment was computed by:

$\Delta By = -\Omega_H \sin(\Psi 0 - 90^\circ)$

and

new By = previous By + Δ By

F. Results

After stabilization in the gyrocompassing mode following the calibration procedure, a ten minute average of the azimuth synchro reading was obtained. This average was 90.04° representing an apparent misalignment error of .04° (2.4 arc minutes) since 90° was the nominal correct reading given the easterly Scorsby orientation.

An estimate was made of the probable azimuth misalignment from North. See Figure 4-3 for Scorsby and platform orientations. The Scorsby roll axis, which is its outer axis, was aligned with true East by survey as described in paragraph 4.2.1. The maximum survey error was 1.8 arc minutes.

The platform is mounted on the azimuth or inner element of the Scorsby. The Scorsby outer axis was rolled ±5° at a sinusoidal frequency of 0.05Hz. The pitch synchro on the platform was monitored. The pitch axis is the outer axis of the platform. The Scorsby azimuth was changed until there was no discernable signal from the platform pitch synchro. At this position the platform's pitch axis was perpendicular to the Scorsby's roll axis to within the tolerance of the synchro readings: Ψ_{sc} = 90 in Figure 4-3. The synchros are specified as being accurate to 20 arc secnds (0.33 arcminutes). With the azimuth synchro having been previously corrected for assembly offsets (see paragraph 4.2.2) the maximum probable error from North in platform heading were taken to be:

$(2.4^2 + 1.8^2 + .33^2)^{\frac{1}{2}}$ = 3 arcminutes

The goal value was 17 acrminutes RMS.

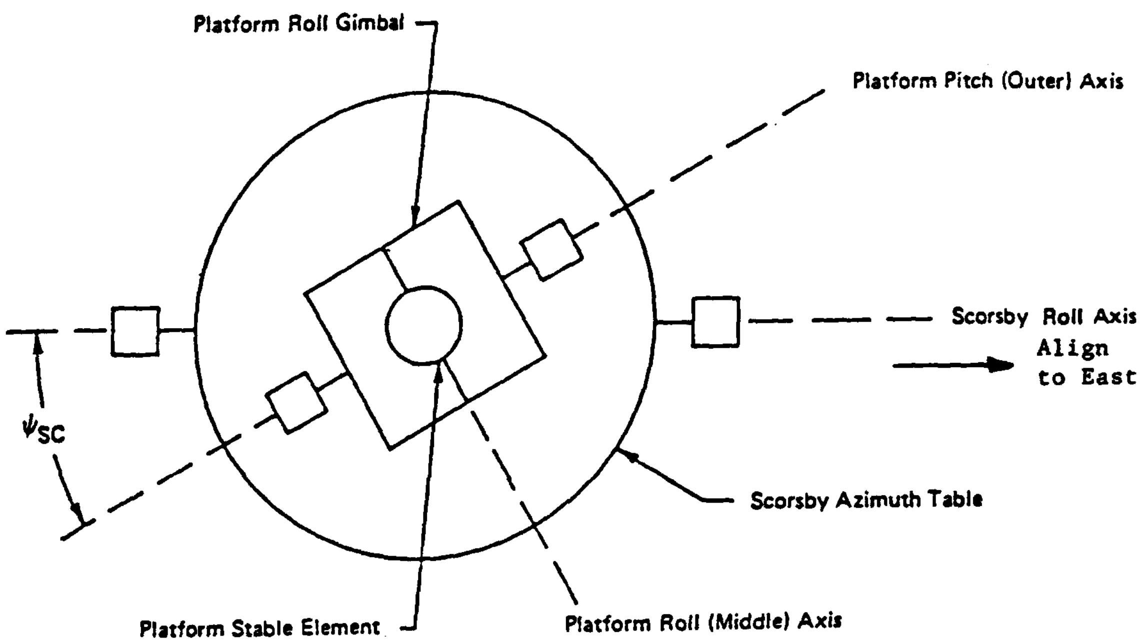
4.2.4 Operation Mode, Navigating Platform

A. General

The purpose of this test was to demonstrate that the platform maintains 30 arc min standard deviation in alignment and 200 meter standard deviation in position error when the platform is operated in the primary navigation mode. The leveling accuracy was not directly checked because it is implied within the position check.

The primary mode requires inputs from the TI 4100 GPS receiver/processor. The test were scheduled such that the primary RUN mode was evaluated when satellites were available.

Figure 4-3. Platform Orientation Scorsby Table



Top View

Figure 4-4 depicts the constraints on satellite availability in the time frame 14-15 February, 1986. The hours of satellite availability on the actual dates of the tests were computed by the rule that the satellites rise four minutes earlier on successive days.

B. Calibration

The testing of Section 4.2.3 Inertial Instrument Calibration were completed before the tests of this section

C. Primary Mode Tests (Satellites Available)

Initialization for these tests were begun prior to the rise of the first satellite. The operator initialized the TI 4100 through its CDU port.

(a) Set the latitude, longitude and MSL altitude of the laboratory. These variables were determined by data collected from the TI 4100 tracking four satellites during initial evaluations. The values used were:

LON 78° 55' 44.7"
LAT 43° 6' 0.94"
MSL 169.2 METERS

(b) Enter the Geenwitch Mean Time, Julian day, Year, and satellite almanacs. The Atomic Clock was always used as the primary time standard and remained ON to ensure thermal stability.

(c) Select TI 4100 NAV MODE 0, the stationary mode.

(d) The platform was operated in the CAGED mode with approximate leveling and alignment as determined by the synchro angles until 4 satellite vehicles (SV) were acquired.

(e) The first four satellites to rise were selected for acquisition through the TI 4100's CDU part.

(f) The Scorsby heading was set such that the platform pitch axis was oriented as shown in Figure 4.3 with the angle $\Psi_{SC} = 70°$. Superimposed via the Scorsby controls were sinusoidal motions with approximate peak amplitudes of 3° at .05 Hz around the pitch axis and 2° at 0.03 Hz around the azimuth axis. These resulted in simulated vehicle motions about the platform axes of:

PLAT PITCH ° = 1.03 sin (.3t)
PLAT ROLL ° = 2.8 SIN (.3t)
PLAT AZ ° = 2 sin (.2t)

(g) When 4 SV's were acquired, the platform was put in RUN MODE A, the primary navigation mode. In this mode the reference latitude and longitude are obtained from GPS.

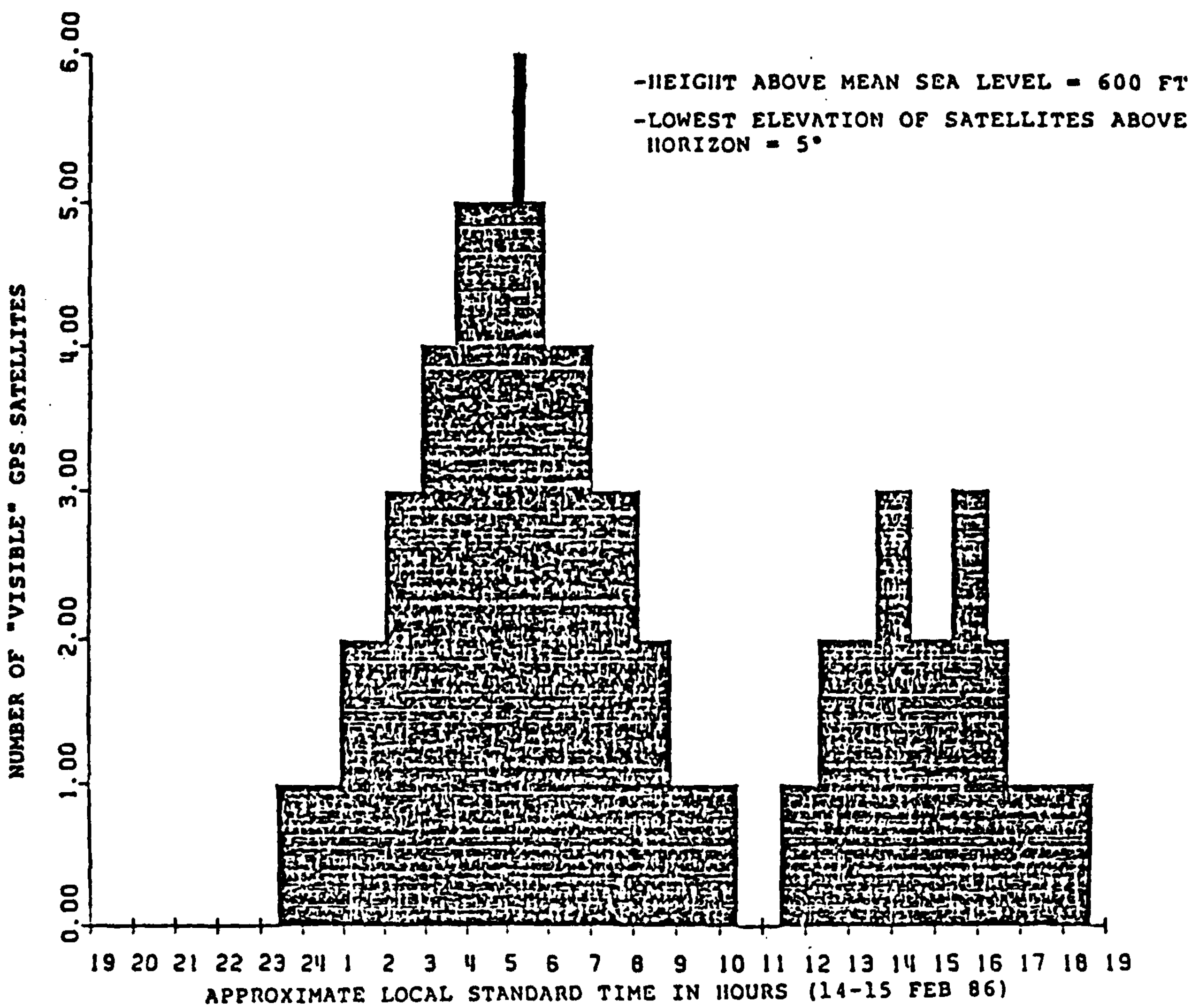
(r) As satellites set, the TI 4100 was successively reprogrammed for 3 and then 2SV operaton. 3SV operation checked performance when "riding" the Atomic Clock and 2SV operation checked performance with the Atomic Clock and Altitude Hold.

(i) When satellites available fell below 2, the GGSS system automatically switched to Free Inertial operation. Drift during this phase was checked.

Figure 4-4. Number of "Visible" NAVSTAR GPS Satellites - Buffalo, New York

14-15 Feb 86

GGSS Phase I Land Test Area



(j) The monitoring of performance in the navigating modes was performed by observing the latitude and longitude variations as indicated by the platform. Since the platform itself was subjected only to angular motion(via the Scorsby table) the actual latitude and longitude are fixed. The variations in latitude and longitude noted are composite errors consisting of the variation of GPS determined latitude and longitude and the platforms response to this variation. GPS latitude and longitude variations are due to changing satellite geometry and the errors of the TI 4100 receiver/processor.

D. Results

Table 4-6 summarizes the test results. In the table, items 3.A,B and C show that after stabilization from the initial satellite lock-on transients, the latitude and longitude variations were well within the 200 meter (656 ft) Standard Deviation allowable limits. For the particular platform initial alignments in this test, the maximum errors during inital lock-on were ±900 (item 3A). If the errors are approximated by a sinusoid decaying in amplitude towards the "after stabilization" values, then the 900' maximum amplitude can be described as a sinusoid of 636 feet RMS value. This is within specification. Item 3.E. shows the results of platform drift after switch to Free Inertial immediately following 2SV control. This is equvalent to .2 NM/HR. for the first 20 minutes. An equivalent of 1.0 NM/HR over this period was the goal.

Table **4-6. Results, Navigating Platform Test**

1. PLAT RUN A WITH SATELLITE REFERENCE & GYRO COMPASSING FOLLOWED BY FREE INTERTIAL

2. SCORSBY MOTION (Aircraft Simulation)

   PLAT PITCH° = 1.03 SIN 2π (.05) t
   PLAT ROLL ° = 2.8 SIN 2π (.05) t
   PLAT AZ° = 2 SIN 2 π (.03) t

3. LAT, LON VARIATIONS

		LON VAR	LAT VAR
A.	INITIAL 4SV LOCK ON (PDOP 3)	±900'	±420
B.	AFTER STABILIZATION (4SV)	±205'	±70'
C.	3SV FOLLOWING B.*	SAME APPEARANCE AS B.	
D.	2SV ALT HOLD	SAME AS B. FOR 15 MINUTES THEN SATELLITES WERE LOST	
E.	FREE INERTIAL	265' IN 22 MIN250' IN 22 MIN	

*With clock accuracy identified by TI4100 from 4SV operation.

4.2.5 GGI Calibration

A. The purpose of this test was to determine the scale factors and phase compensation which minimized errors in the gradient measurements of *the 3 GGI's.*

B. Prior to these tests, the GGI's were groomed in the GGI Laboratory. Each instrument was set up individually using the same electronics. This procedure assured check of the GGSS electronics against the laboratory standard. The tests of section 4.2.3 were completed prior to beginning this section.

Additional grooming which was a necessary presequisite to all GGI laboratory tests was performed at this time. These were:

1. Motion Sensitivity GGI Compensation

   A. $\Sigma\alpha_o$ - 2Ω motion sensitivity along this spin axis. A 2Ω ($\frac{1}{4}$ Hz) signal was induced in the roll axis of the Scorsby table along each GGI spin axis. The $\Sigma\alpha_o$ integration was adusted for a minumum Δ change of the I/L and cross gradients for the GGI spin axis normal to, and 180° from this position.

   B. K4, K8 - 1Ω sensitivity along the spin axis of the GGI. A 1Ω ($\frac{1}{8}$ Hz) signal was induced in the roll axis of the Scorsby table. K4, K8 were set for mimimum Δ change in the gradient signals for the GGI spin axis normal to and 180° from the Scorsby motion.

   C. K2, DIFFK2 - 2Ω motion sensitivity perpendicular to the spin axis. A 2Ω signal was induced in the roll axis of the Scorsby table. Each GGI was positioned such that the motion of the Scorsby was perpendicular to the spin axis: K2, DIFFK2 was adjusted to minimize the Δ change of the gradient signals perpendicular to and 180° from the motion perpendicular to the GGI spin axis.

2. GGI Demodulator Phase Checks System Level

   A. Wa (Axial Shake) - The axial shake demodulator reference was changed at the LCMP drawer. The $\Sigma\alpha_o$ demodulator output was monitored with a chart recorder. The axial shake reference was varied until a maximum peak to peak amplitude of the $\Sigma\alpha_o$ was determined from strip chart recordings.

   B. Ws - The Ws phase reference was adjusted at the LCMP drawer for a maximum Ws demodulator output as observed by a chart recorder.

C. 2Ω - A 5 minute average of the I/C and cross gradients was acquired at the Rolm computer terminal and recorded. A dc bias shift was inserted singly into each gradient channel. A 5 minute average was recorded. The 2Ω phase reference was varied until the dc bias shift was seen only in the channel it was inputed. To determine the demodulator phase reference change

$$\tan^{-1} = \frac{\text{gradient O/P}}{\text{gradient O/P w/bias shift}}$$

D. 1Ω and 3Ω demodulator outputs from the LCMP drawer were monitored when a dc shift was applied to the 1 Ω intergrator input. The 1Ω intergrator was changed until the 1Ω demodulator output showed the maximum output change while the 3Ω demodulator output showed minimum change.

3. K4, K8, K2, DIFFK2 and $\Sigma\alpha_o$ Compensation

To adjust the listed compensations to motion sensitivity the platform was caged and in low gain.

A. K4, K8, $\Sigma\alpha_o$ compensation - a spectrum analyser was connected to the band pass output ofthe instrument. With a horizontal motion induced by the shaker at 1.2 HZ the peak amplitude at 1.2 HZ + .25 HZ and the peak amplitude at 1.2 HZ - .25HZ was adjusted to a minimum by putting a bias shift into the K4, K8 $\Sigma\alpha_o$ integrator offset inputs to the LCMP drawer.

B. K2, DIFFK2 compensation - The shaker mechanism was set up for vertical motion at a frequency of 2.2 HZ. The peak amplitude at 2.2 +.25 HZ and 2.2 - .25 HZ is adjusted to a minimum by adjusting the K2, DIFFK2 integration offset inputs at the LCMP drawer.

C. Procedure

The platform was step indexed in 30° increments for a complete revolution. A 5 minute average for the I/L and cross gradients for each instrument was recorded at each increment. A mean average was determined for each gradient for 1 revolution.

The platform was then carouselled at 500°/hr for a complete revolution. The average output while carouselling for the I/C and cross gradients was recorded. The difference of the gradient average between the step indexing and the constant carousel rate was used to determine the scale factor of the instruments.

D. Results

The axial shake frequency (w_a) was changed from 1.58 HZ to 1.47 HZ to reduce a 20 second period observed on locations 1 and 3. Table 4-7 summarizes the results of the pre-test grooming. The scale factors and phase compensation angles are used in off-line data reduction programs to extract the gradients from the GGI measurements. The processing of data to determine the scale factor(s) is outlined in this section as well as the processing of data to measure the misalignment angle (ϕ_3). The misalignment angle is one component of the phase compensation angle. Other components are due to factors in the electronics which contribute addtional phase variations. The methods for determination of the total compensation are not shown but the results listed.

GGI #	S	PHASE ANGLE
1	.634	84°
2	.6111	79.11°
3	.6168	76.55°

The procedure for determining S and ϕ_3 follows:

1. Definitions

ΔW_c = Mean {GGI Sys Cross Carousel - GGI Sys Cross Indexed}

ΔW_I = Mean {GGI Syst Inline Carousel - GGI Sys. Inline Indexed}

Means are over one carousel period or over 360° of carousel angle.

Ideally (perfect GGI scale factor and align).

$$\overline{\Delta W}_c = 1/3\ [\,W_C^2 - 2\Omega\ W_c \sin\phi\,]\ .10^9$$

$$\overline{\Delta W}_I = 0$$

Where

$\Omega = 7.292115\text{X}10^{-5}$ R/S earth rate

ϕ; Latitude

$W_c = 500 \dfrac{\pi}{(180)\ (3600)}$ carousel rate

2. Updated GGI scale factor is

$$S_n = 1/3 \frac{[W_C^2 - 2\Omega\, W_C \operatorname{Sin} \phi] \,.10^9}{[\overline{\Delta W_C}^2 + \overline{\Delta W_I^2}]^{\frac{1}{2}}} S_o$$

Sn, So - new, old factor

3. GGI misalignment about spin axis given by

$$\phi_3 = \tfrac{1}{2} \operatorname{Tan}^{-1} \left(\frac{- \overline{\Delta W_I}}{\overline{\Delta W_Q}} \right)$$

TABLE 4-7

MOTION SENSITIVITY (E/MG)

1Ω
2Ω PERPENDICULAR SPIN AXIS ($\sum\alpha_{\Omega}$)
2Ω ALONG SPIN AXIS (DIFF K_2)

	GGI I/L	LOC 1 CR	GGI I/L	LOC 2 CR	GGI I/L	LOC 3 CR
1Ω	.11	.08	.16	.12	.2	.16
2Ω	.5	.25	.6	.6	.3	.3
2Ω	.03	.68	.06	.5	1.01	.06
3Ω	<3.0*	<3.0*	<3.0*	<3.0*	<3.0*	<3.0*

* Not adjustable - based on GGI Grooming Experience

4.2.6 SYSTEM NOISE PERFORMANCE STATIC

A. Purpose

The purpose of this test and the tests of section 4.2.8, System Noise Performance, Dynamic is to verify that the total system noise is sufficiently low that the quality of the gradient measurements can satisfy the requirements of obtaining gravity anomalies with an accuracy of 0.18 arc sec and 0.9 mgals.

B. Prerequisite Calibration/Adjustments

The tests and calibration of section 4.2.5 were completed prior to the tests of this section.

C. Test Procedure

The static tests of this section were conducted with no external motion (i.e., a static Scorsby table) and the platform in the Navigating Mode. The power spectrum of the three inline and the three cross gradients in the umbrella system were measured. The high frequency white noise due to the GGI self-noise and the effects of the unwanted platform motion resulting from the accelerometers, gyros, and control system performance were determined.

The PSD routine is described in detail in the System Test Plan, Bell Report No. 6469-928004 Rev. D, Nov 1985. The PSD record lengths, filter bandwidths,and fundemantal are summarized.

Signal	i selected (Sample interval Δt in seconds)	record Length	Freq. Range Designations	Filter Bandwidth (rad/sec)	Fundamental Harmonic (rad/sec)
X_1	2	34.133 Min.	HIGH	N/A	0.30680E-02
X_5	32	9.1022 Hrs.	MID	0.0196	0.19175E-03

D. Results

The static high frequency noise PSD's (E^2/R/S) measured were:

LOC1		LOC2		LOC3	
I/L	CR	I/L	CR	I/L	CR E^2/RAD/SEC
59	45	44	41	31	27

The goal of less than 100 E^2/R/S was met.

4.2.7 Self-Gradient Determination

A. General

The purpose of this procedure was to measure the gradient components due to platform and Scorsby angular positions. The data was used on a "post-procedure" basis to determine coefficients of a mass model which is subsequently used to compensate for equipment self-induced gradients. This was the first of two procedures needed for complete determination of all coefficients; the second procedure was done at system/vehicle integration and accounted for vehicle masses. See section 4.4 and 4.6. The compensation is used in both "operational" and post-mission "stage 1" processing software and will be used in both places.

Gradients caused by the mass of elements physically located within the Gravity Gradiometer Survey System, or by the vechicle structure and contents, are referred to as self-generated gradients. These errors must be removed (compensated for) during Gravity Gradiometer Survey System operation to the extent necessary to meet performance requirements.

In order to visualize the self-gradient problem in more detail, consider the following structures encountered moving outward from the instrument cluster.

1. Roll gimbal and associated torquer, synchro, bearings, etc.

2. Pitch gimbal and associated torquer, synchro, bearings, etc.

3. Platform frame, enclosure,and surrounding mass structure which is be the survey vehicle for actual surveys and was the Scorsby table in the laboratory.

The first two of these, although fixed as to form and mass, produce instrument output variation due to their attitude variations relative to the stabilized instrument cluster. Structure 1 varies in azimuth with respect to the instrument cluster, while 2 varies in both azimuth and pitch. The third structure also produces instrument output variations with attitude but, in addition, presents problems associated with shape and mass variations; viz, fluid tanks, movable equipment such as elevators or control surfaces, etc. These latter are processed offline on the basis of recorded data and are not part of the tests of this section.

The structural elements of the Gravity Gradiometer Survey System that are positionally fixed to the stabilized gradiometer instrument triad, essentially affect only the bias of the gradiometer instruments and therefore, do not introduce a problem. Elements that rotate with respect to the stabilized triad such as the enclosure, the platform gimbals, etc., introduce gradient errors as a function of attitude.

B. Prerequisite Tests/Calibrations

Prior to the beginning of this test, the tests of section 4.2.6, System Noise Performance Static, were completed.

C. Test Procedures

The GGSS platform was operated in the PLAT RUN E mode. The Scorsby was rotated in azimuth in 30° steps for 360°. At each step the heading of the platform was redirected to North by the platforms azimuth synchro control. The platform leveled on it's own accelerometers. Further, at each Scorsby heading, the Scorsby was rolled ±8° in 2° steps. At each of the Scorsby positions, the system was allowed to settle for 180 seconds and then, the three cross and three inline gradients in the GGI umbrella system were read at 2 sec intervals for 300 seconds. These readings were then averaged and stored with the Scorsby angles.

This provided gradient variations which were functions of the GGI position with respect to mass elements in the platform.

D. Results

The data was reduced to model the self gradients as a function of the vehicle attitude angles. Figures 4-5 through 4-16 show the resulting gradients modelled as functions of azimuth, pitch and roll angles.

4.2.8 System Noise Performance, Dynamic

A. General

The tests of this section were conducted with Scorsby table motion to assess the additional contribution to the GGI noise due to platform dynamics and acceleration. In addtion, the efficiency of the gradient compensation was validated.

B. Prerequisite Calibration/Adjustment

The tests and calibration of section 4.2.7 were completed prior to the tests of this section.

C. Test Procedure

This was the same as for section 4.2.6 with an additional simulation of ship's motion. The ship's motion was simulated by the Scorsby table as descrbed in section 4.1.4.

D. Results

The high frequency white noise levels as determined by the PSD including all error sources were:

DYNAMIC NOISE PERFORMANCE (E^2/R/S)

LOC 1		LOC 2		LOC 3	
I/L	CR	I/L	CR	I/L	CR
109	83	32	28	44	41

The goal for white noise levels in each gradient was that it not exceed 190 E^2/R/S. The goals was met. Figure 4-17 shows the PSD of the typical spectrum of the GGI's.

FIGURE 4-5

INLINE 1 TOTAL SELF GRADIENT COMPENSATION ROLL -8 +8

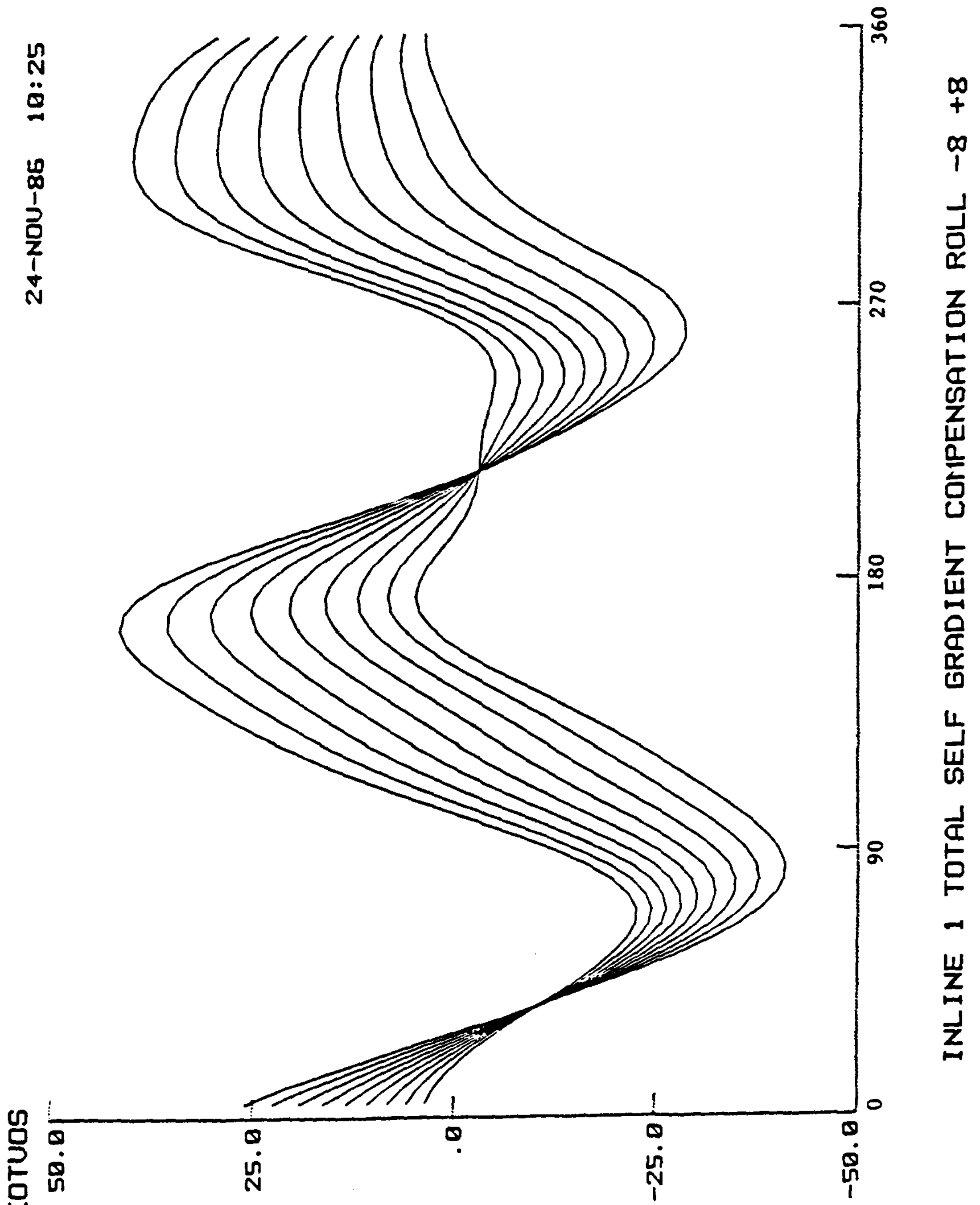


FIGURE 4-6

INLINE 2 TOTAL SELF GRADIENT COMPENSATION ROLL -8 +8

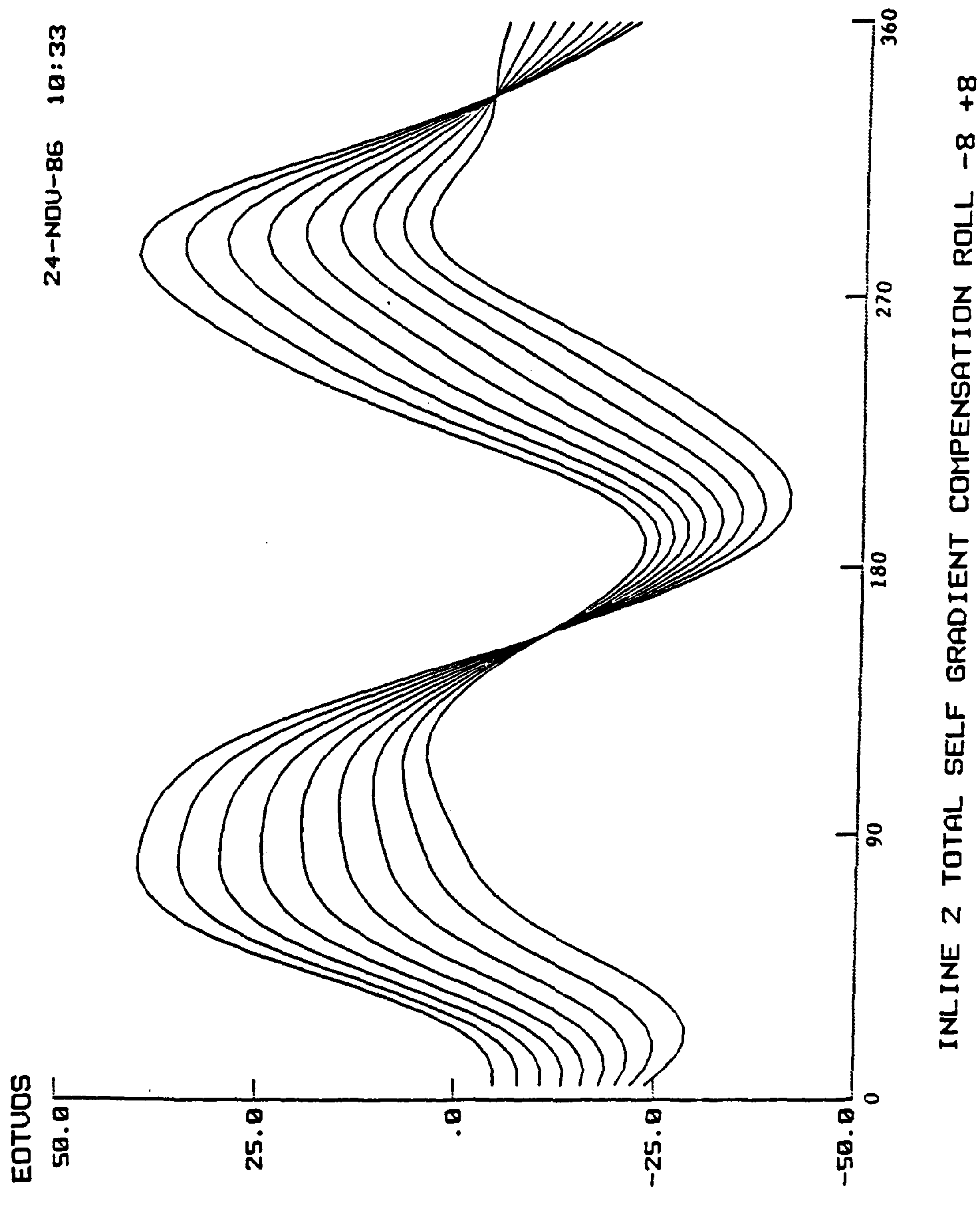


FIGURE 4-7

INLINE 3 TOTAL SELF GRADIENT COMPENSATION ROLL -8 +8

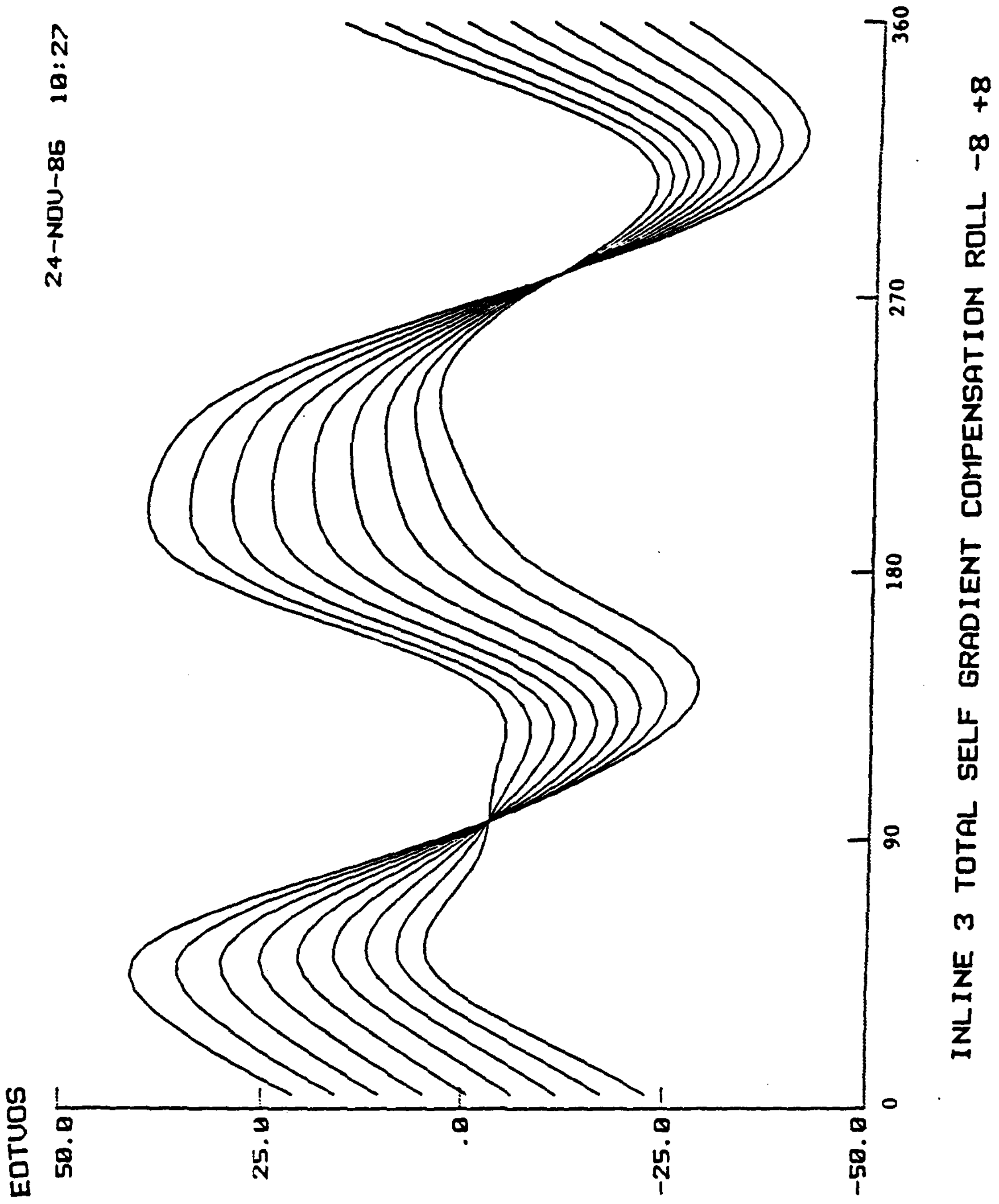


FIGURE 4-8

CROSS 1 TOTAL SELF GRADIENT COMPENSATION -8 +8

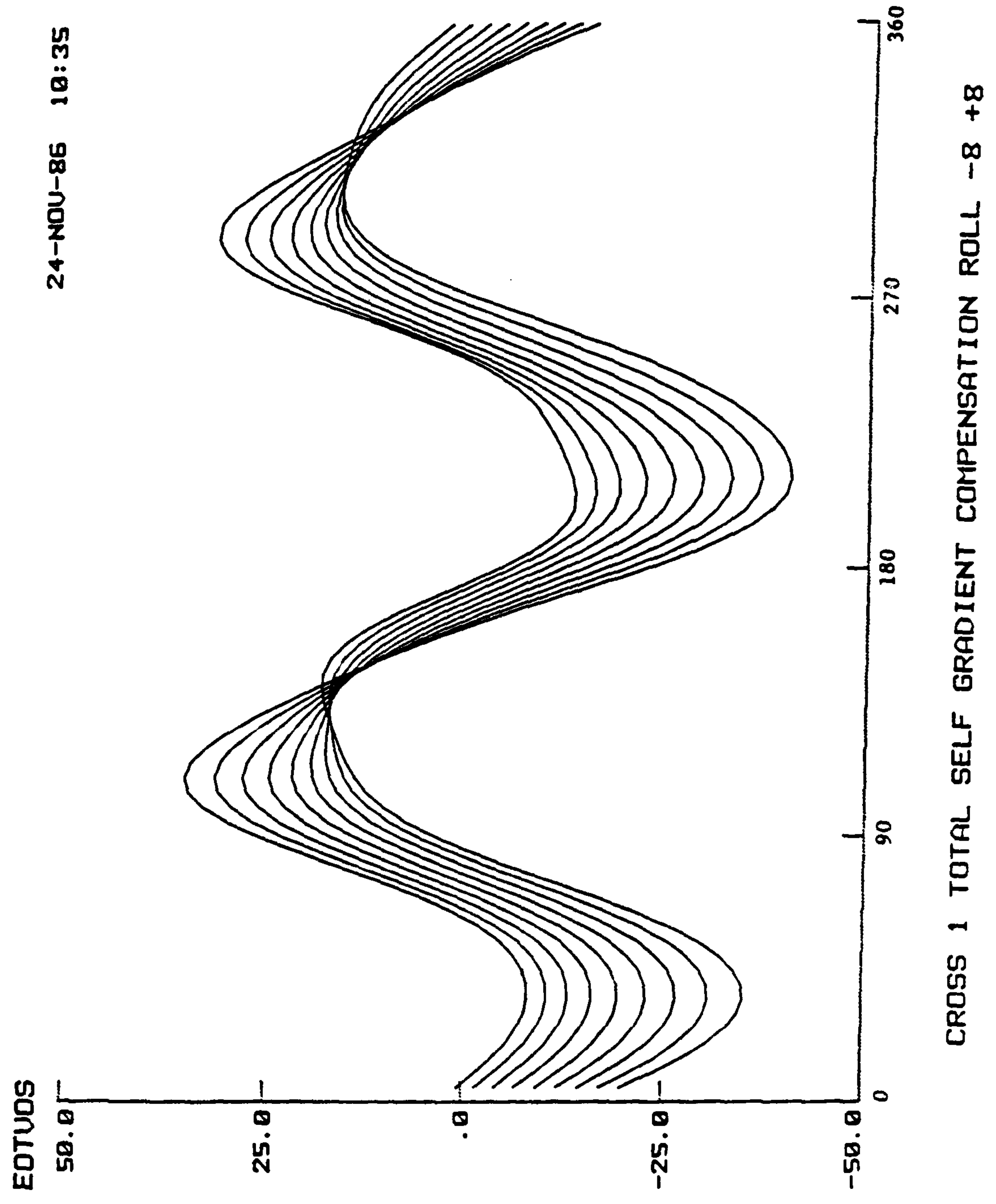


FIGURE 4-9

CROSS 2 *TOTAL SELF GRADIENT* COMPENSATION ROLL -8 +8

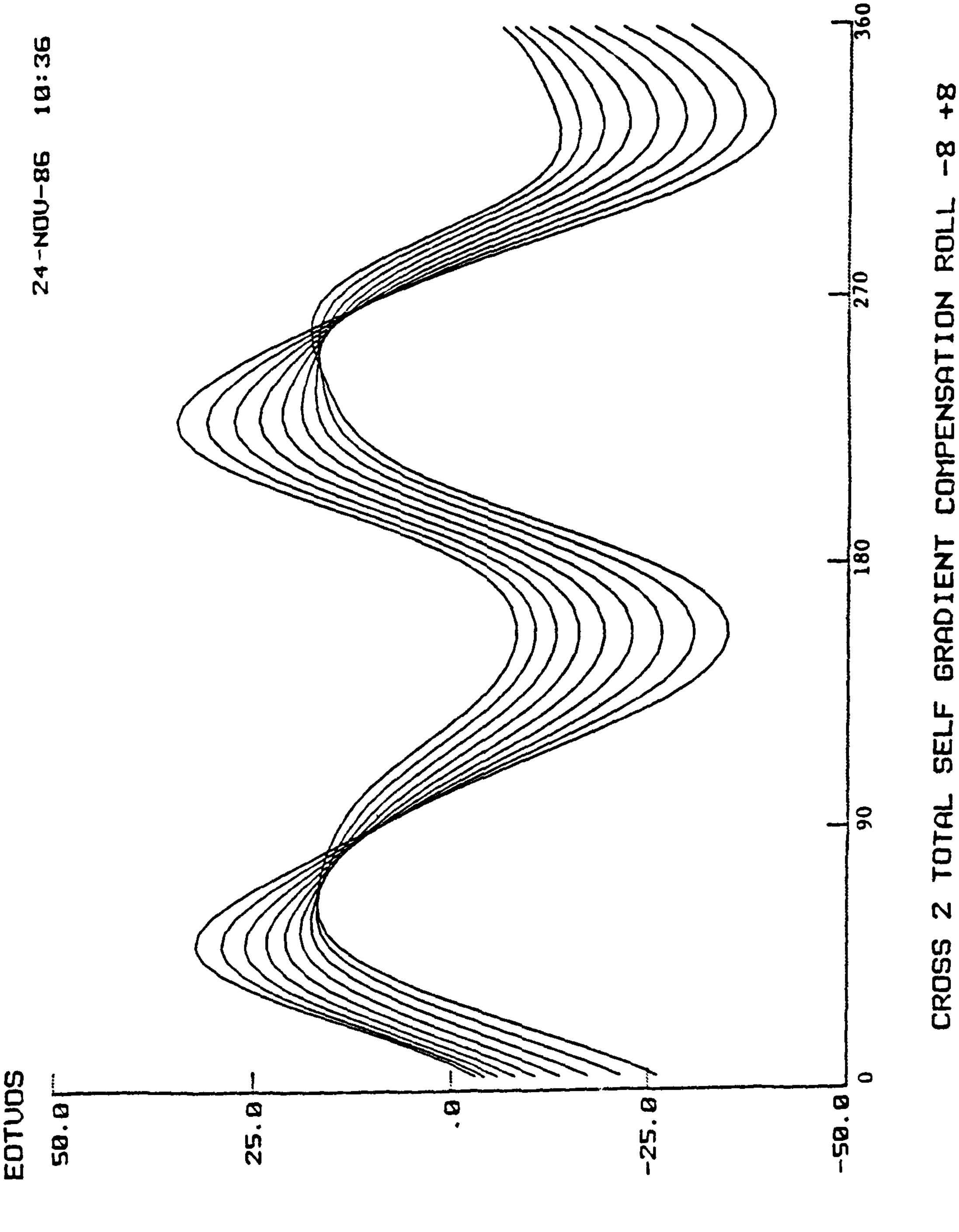


FIGURE 4-10

CROSS 3 TOTAL SELF GRADIENT COMPENSATION ROLL -8 +8

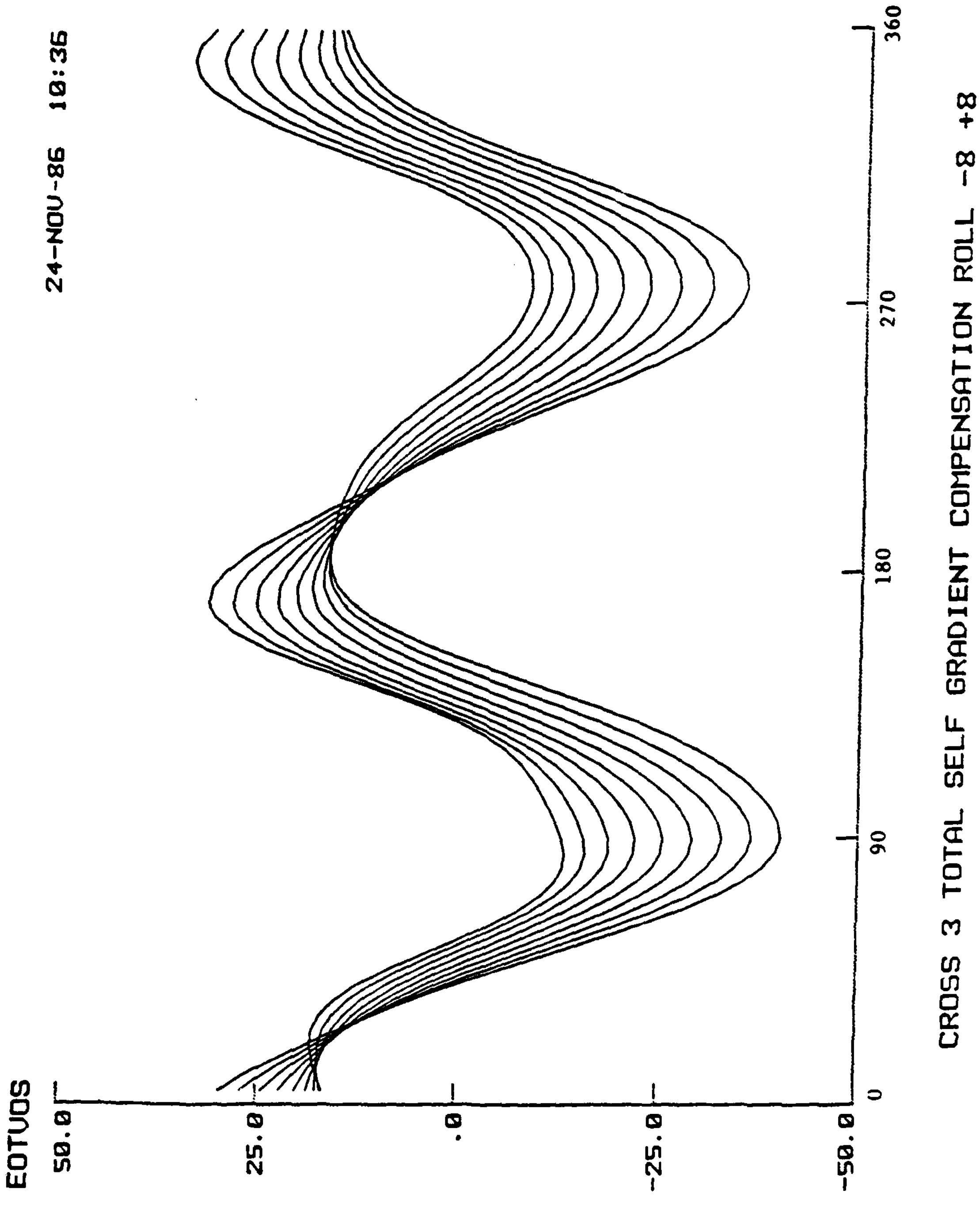


FIGURE 4-11

INLINE 1 TOTAL SELF GRADIENT COMPENSATION PITCH -8 +8

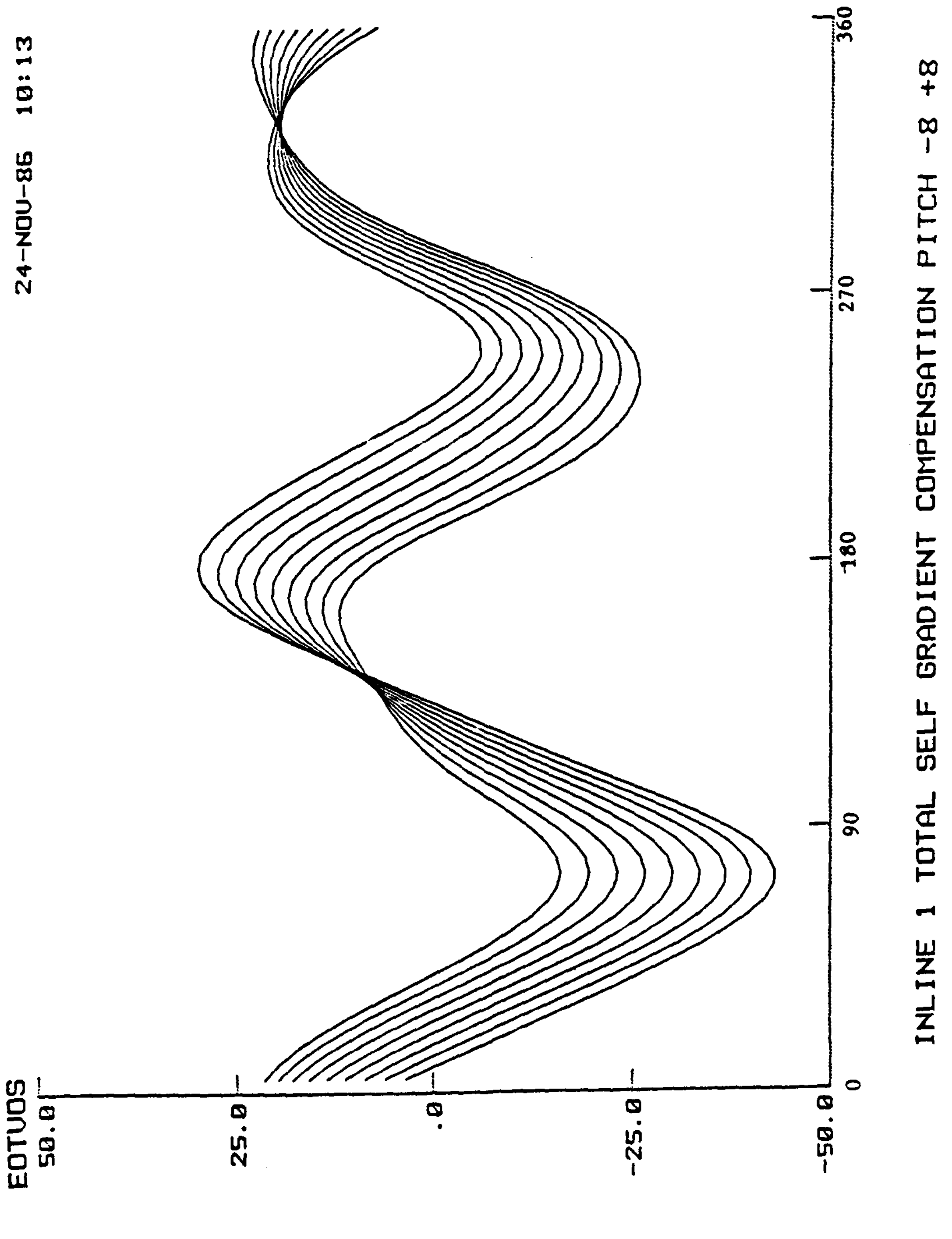


FIGURE 4-12

INLINE 2 TOTAL SELF GRADIENT COMPENSATION PITCH -8 +8

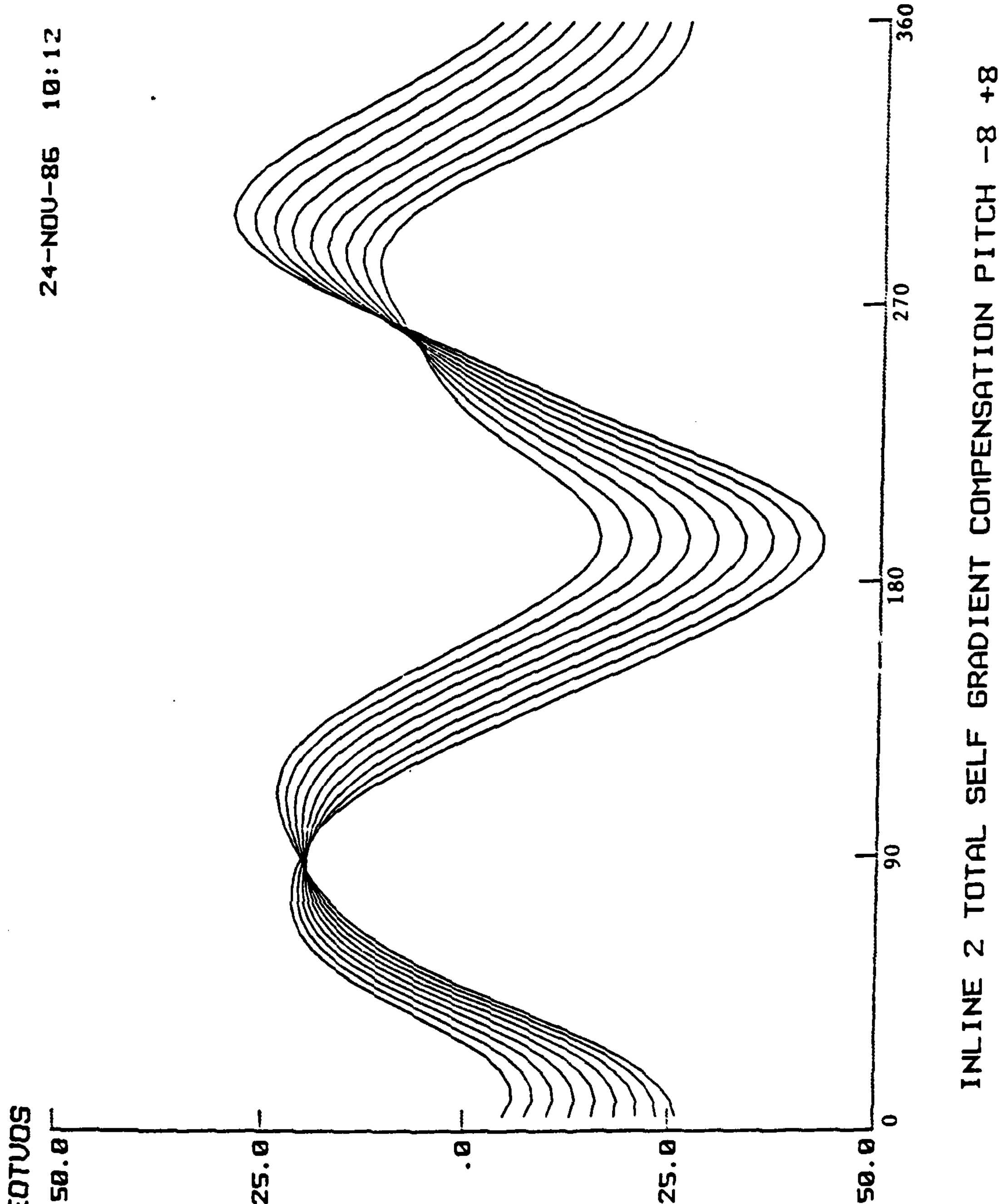


FIGURE 4-13

INLINE 3 TOTAL SELF GRADIENT COMPENSATION PITCH -8 +8

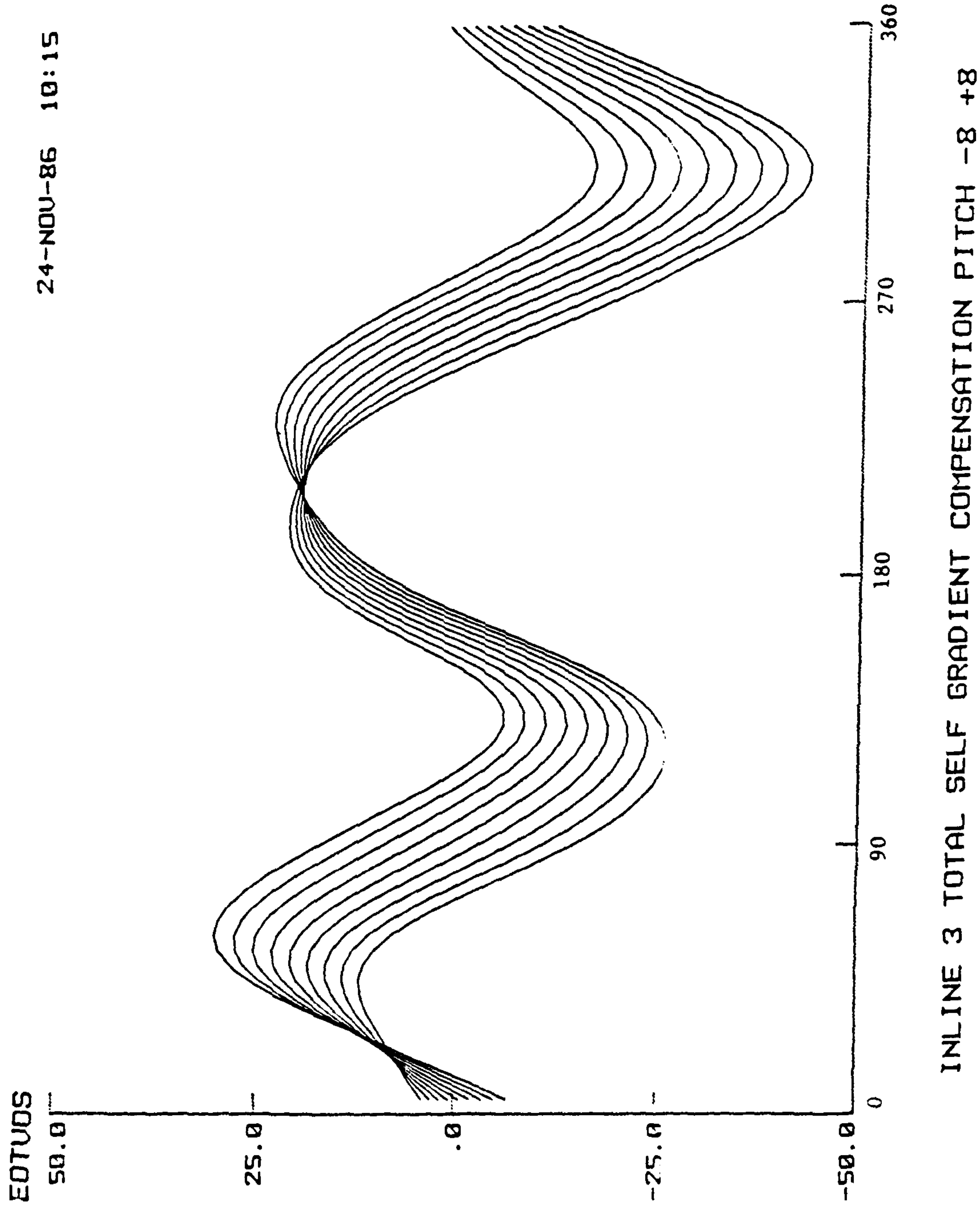


FIGURE 4-14

CROSS 1 TOTAL SELF GRADIENT COMPENSATION PITCH -8 +8

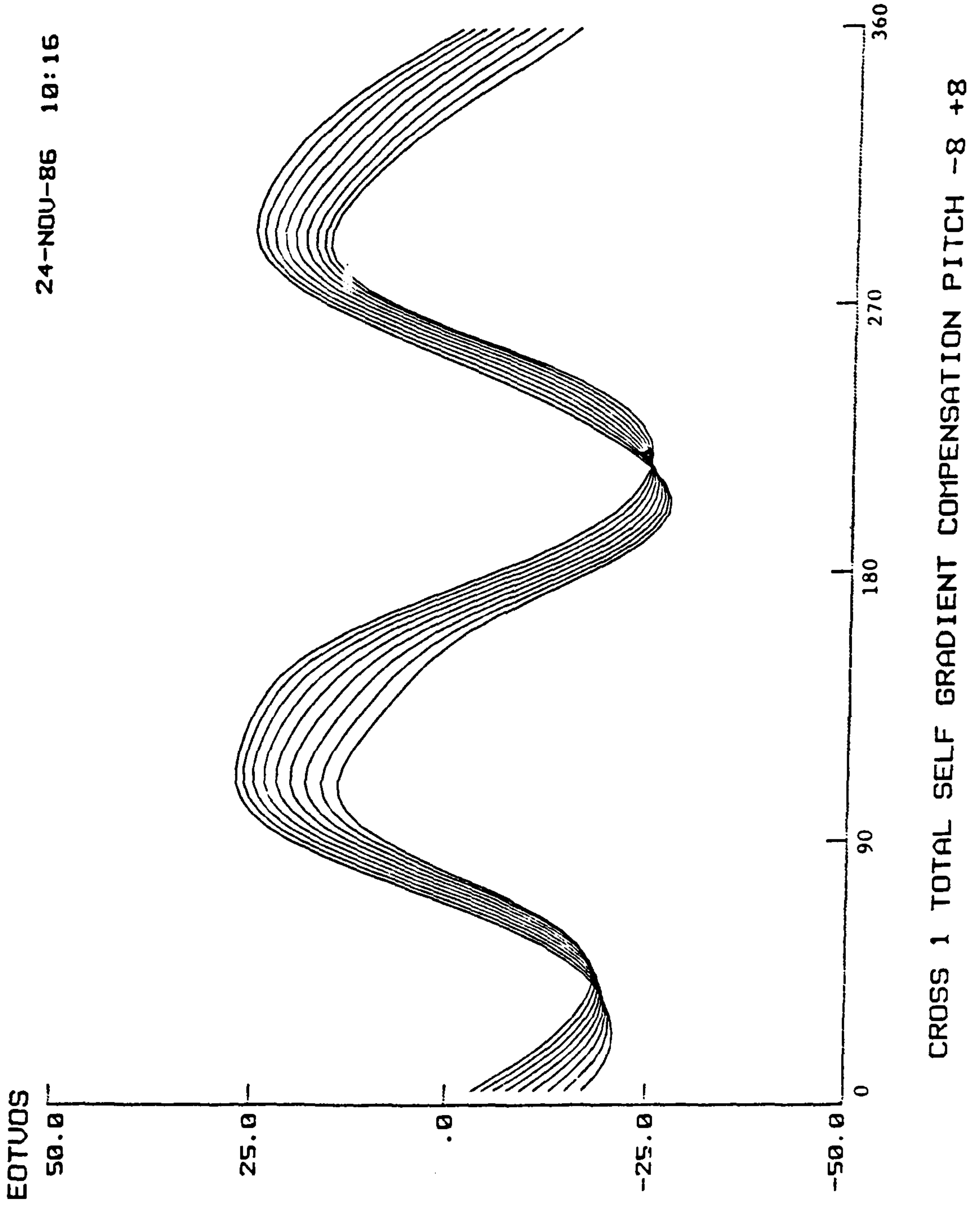


FIGURE 4-15

CROSS 2 TOTAL SELF GRADIENT COMPENSATION PITCH -8 +8

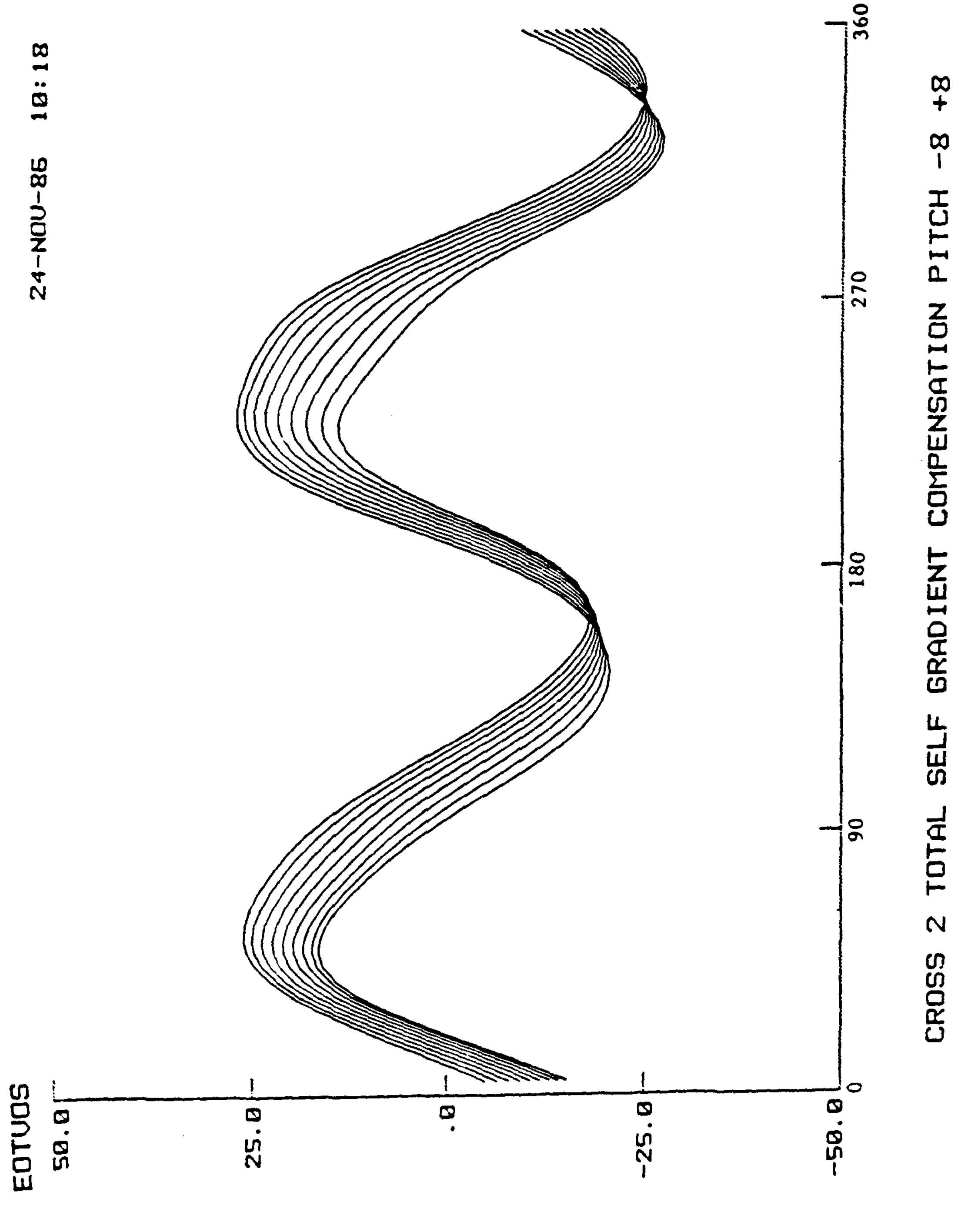


FIGURE 4-16

CROSS 3 TOTAL SELF GRADIENT COMPENSATION PITCH -8 +8

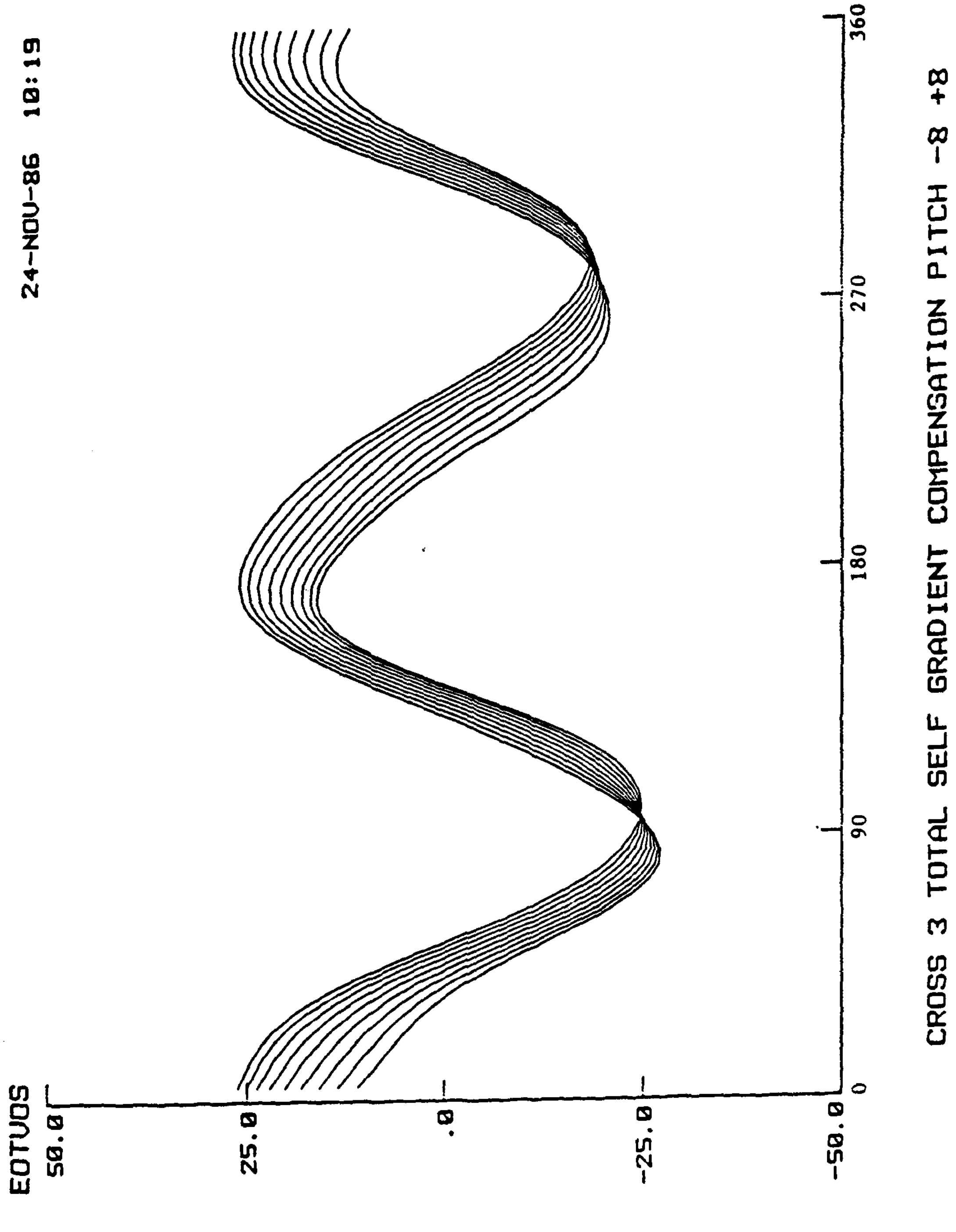
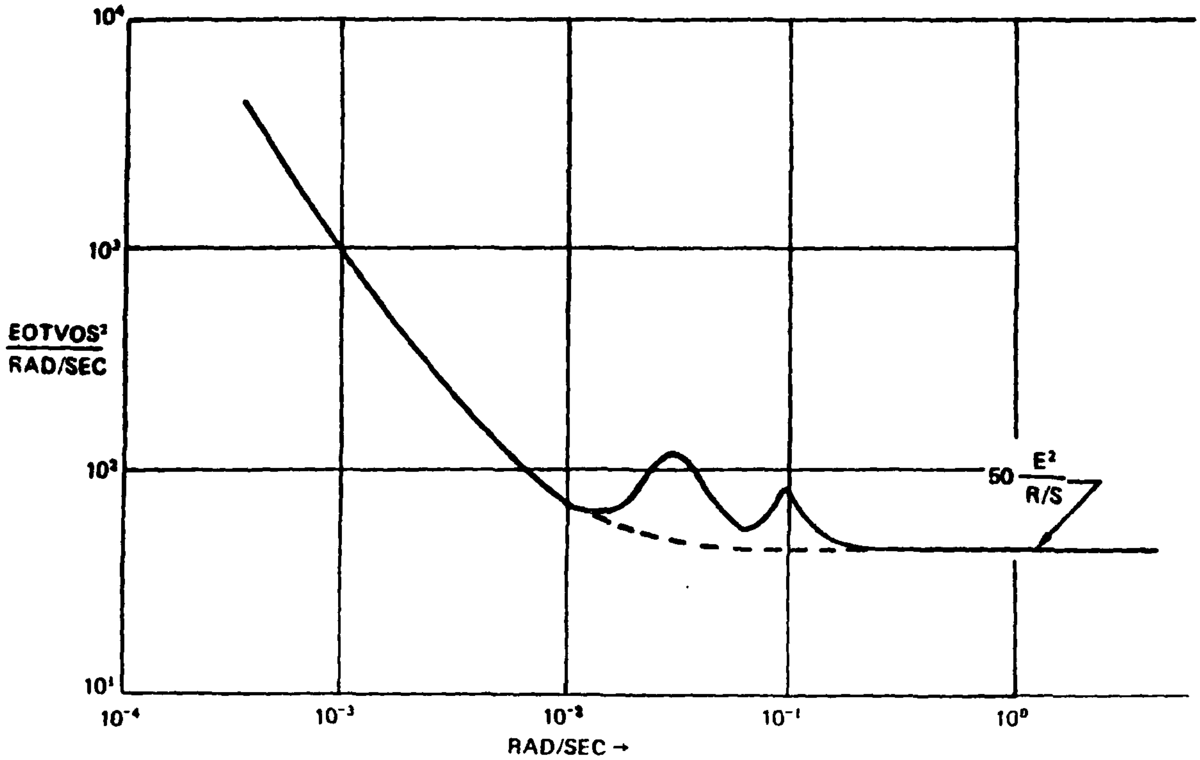


FIGURE 4-17

TYPICAL SYSTEM NOISE PERFORMANCE DYNAMIC SCORSBY TEST



4.3 Land Vehicle Installation and Gradient Calibration

4.3.1 General Approach

The controlling document for the procurement of the land vehicle for GGSS was Land Vehicle Specification for Bell Gravity Gradiometer Survey System, Report No. 6496-947007D, Dec. 1985.

The documents which defined the required rework of the selected vehicle for the purpose of installing the GGSS equipment were:

• Bell Drawing 6496-360250	GGSS Land Vehicle
• Bell Drawing 6496-360200	GGSS Land Vehicle Installation
• Bell Drawing 6496-826502	Cabling Diagram - AFGL- GGSS
• Bell Spec 6496-947006	Specification for GGSS Uninterruptable Power Supply and GGSS Electrical Load Center

Criteria in the selections were:

- Volume and weight capacity
- Power generating equipment
- Environmental controls
- Ride qualities (vibration, acoustic noise, sway)
- suitability for airborne transport (clearance for C-130 on-off loading, tie downs, crashworthiness)

After due consideration of tractor-trailer, straight-type,and van type trucks, an "RV" or "Motor home" type vehicle configuration was chosen as most appropriate for the AFGL GGSS. These vechicles have a wider suspension stance and lower C.G. than a truck, which results in less sway when underway. High frequency vibration and acoustic noise are lower.

The vehicle selected was a 33-foot Revcon Motor Coach manufactured by Revcon Inc. of California. This vehicle had distinstive features which were attractive for the GGSS application such as a tandem rear wheel layout and softride qualitites. Front wheel drive eliminated the drive shaft to the rear wheels and permitted a deep, flat floor construction. This increased volume availability while retaining a low C.G. when loaded. A general installation description follows:

The GGSS Element that senses the Gravity gradient is the Gravity Gradiometer Instrument (GGI). The GGIs are carried on the innermost (3-axis stabilized) gimbal of the GGSS Platform which is, in turn, mounted within an enclosure producing temperature control and vibration isolation. This equipment, along with 5 electronics racks and an Uninterrputible Power Supply (UPS) Console, were installed within the Revcon Motor Coach.

The layout features the location of the platfrom enclosures between the axles to minimize suspension induced accelerations. Shorter equipment racks were placed over the wheel wells. The recorder rack was located to be visually accessible to test personnel riding in the passenger seat. This facilitated monitoring of system vital signs during a test traverse.

The coach was outfitted with power generating equipment, heaters, air conditioning, operators station, CB radio and cellular telephone. Thus equipped, the coach is a self-contained mobile system capable of conducting gravity gradient surveys over most road surfaces.

The coach was equipped with external connectors to accept outside power to support continuous operation of the GGSS when the coach is parked. The GGSS is intended to be powered-up 24 hours a day, when on a survey mission, to maximize reliability and avoid thermal start-up transients. On-board batteries work in concert with UPS to provide continuous power during switchover from one raw power source to another.

The land system was designed to adapt rapidly to airborne surveys. The GGSS is readily transformed into an airborne survey system by driving the Revcon Coach onto a C-130 Hercules Aircraft that has been prepared with an umbilical cable which connects to the coach. The cable supplies power to the coach (and GGSS) as well as signal & communications links between the GGSS and aircraft. The coach is mechanically secured inside the aircraft by chains that attach from chassis-mounted shackles under the coach to standard array of tie-down rings on a cargo compartment floor of the C-130. Details of the airborne installation are presented in section 4.5.

4.3.2 Detailed Description

The following is a list of equipment modules that comprise the Gravity Gradiometer Survey System:

- Platform/Enclosure Assy
  - 3-Axis Platform
  - 3 GGIs
  - Thermal Enclosure
  - Air Conditioner
  - Vibration Isolators
  - Floor-Mounted Skid
- Rack No. 1 (GGI Electronics)
- Rack No. 2 (Platform Electronics)
- Rack No. 3 (Tape Drive and GPS Receiver)
- Rack No. 4 (System Power Supplies and Computer)
- Rack No. 5 (Scopes and Chart Recorders)
- Aircraft Flight Control/Display Modules
- UPS Console
- Terminal (CRT/Keyboard)
- Printer
- Interconnecting Cable Set
- 33 Foot Customized Revcon Coach
  - Heater/Air Conditioners
  - 15 KW Generator (Gas Engine, 30 Amp Output)
  - 6.5 KW Generator (Gas Engine, 20 Amp Output)
  - Battery Set (Project UPS Back-up)
  - GPS Antenna (Stowable)
  - Fifth Wheel Assy
- Installation and Maintenance Kit (Tools and T/E)

Further detail on the GGSS Equipment hierarchy is seen in Figure 4-18 (GGSS Equipment Matrix).

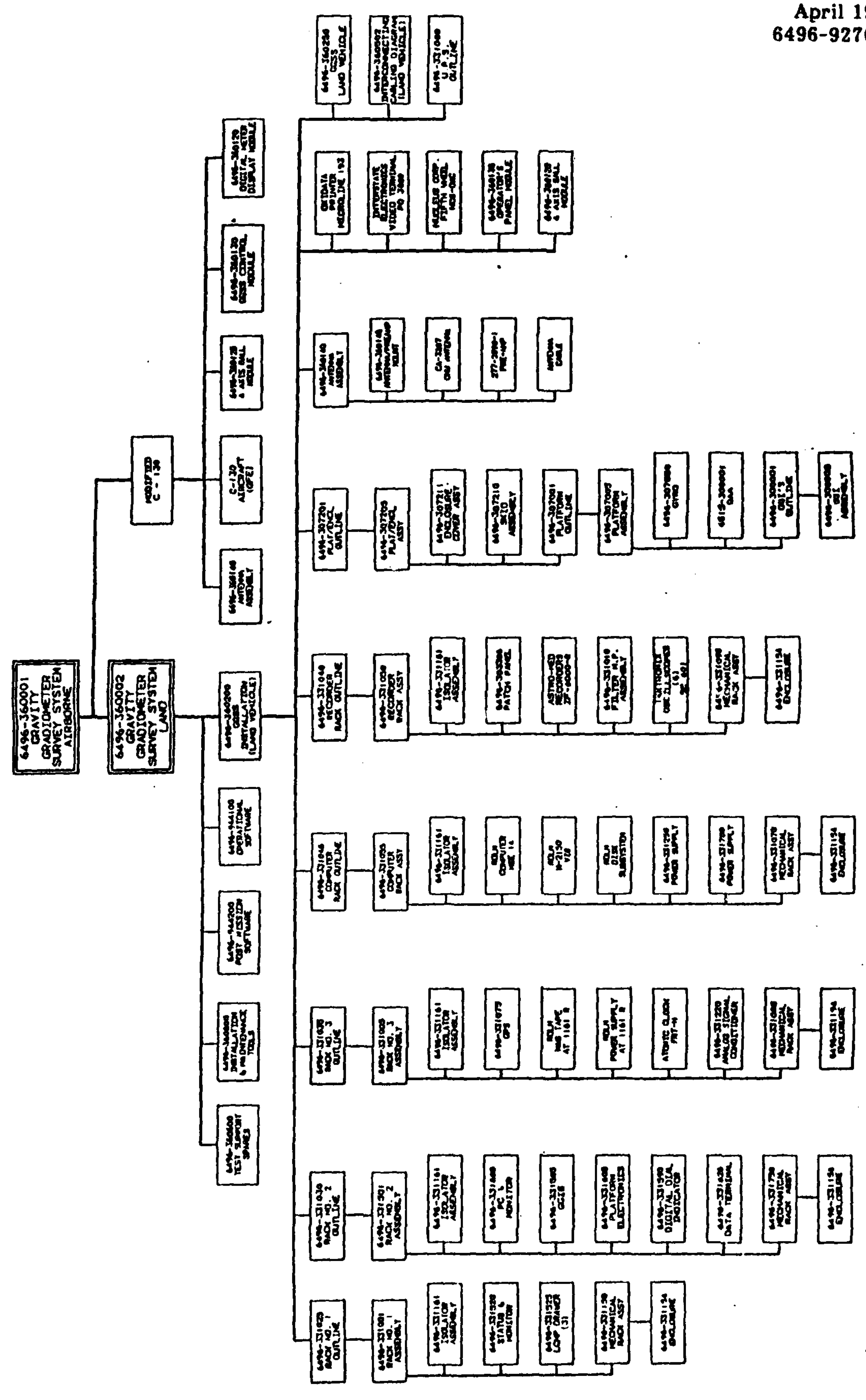


Figure 4-18
GGSS Equipment Matrix

Figure 4-19 is a detailed layout of the equipment within the Revcon van.

Figure 4-20 is view of the van interior facing foward from behind the platform enclosure. The top of the platform enclosure is seen in the foreground. The drivers seat and the van's windshield are seen in the rear of the photograph. In mid field are seen two computer keyboards and monitors. The left hand keyboard and monitor was a temporary set-up using a Data General Dasher 300. This video terminal has editing capabilities and was used while software changes were being made. The video terminal at the right of the photograph is Interstate Electronics Alpaha Display Terminal PD 3000 which is a militarized video terminal to be used in ultimate survey appliations where ruggedness is desirable and no software revision capability is necessary. The keyboard in any case, is used to enter operator selectable parameters and to call up selected paramaters for monitoring.

Next to the militarized display is a display panel used during airborne surveys. Figure 4-21 shows the militarized terminal and the airborne display in close-up. The airborne display is connected in parallel with similar instruments on the pilots cockpit when the van is installed aboard the C-130 survey aircraft. It enables the GGSS terminal operator to monitor pitch and blank commands that the GGSS is sending to the aircraft auto pilot and to monitor lateral and vertical flight path deviations. These are displayed on a 4-axis ball shown on the aircraft display. The lower three rectangles are the digital displays which show the operator the aircrafts ground speed, range and time respectively.

Figure 4-22 is a view of the van interior looking towards the rear from the front of the platform enclosure. The platform enclosure is the large, approximately cubical shape in the foreground. The air conditioner inlet to the enclosure can be seen as the cylindrical duct to the right of the enclosure. At the left, shown open, is the main loading door at the vans side. The rear of the photograph shows the various electronic racks. The rack seen full face in the back of the van is the 16 channel recorder. Selected system parameters are displayed for on-line, real time monitoring.

Figure 4-23 is a view from outside the van looking into the van through the main loading door located at the vans right side. Again, the approximately cubical platform enclosure dominates the photograph. To the left and rear of the enclosure is electronic rack no. 4. This rack contains the D/A and A/D converters which are the links between the ROLM computer and the other subsystems. It also contains the MSE14/A computer itself, disk subsystem and computer power supplies. To the left of this is one of the power consoles. Figure 4-24 shows the electronic racks at the rear of the van. The view is taken from just inside the rear door at the left side of the van. In the foreground is, electronic rack no.1 which contains the off platform GGI electronics. the center rack is the 16 channel recorder. The far rack contains the platform control electronics and the buffers which are the links to the ROLM A/D and D/A converters.

Figure 4-19

GGSS-Land Vehicle Installation

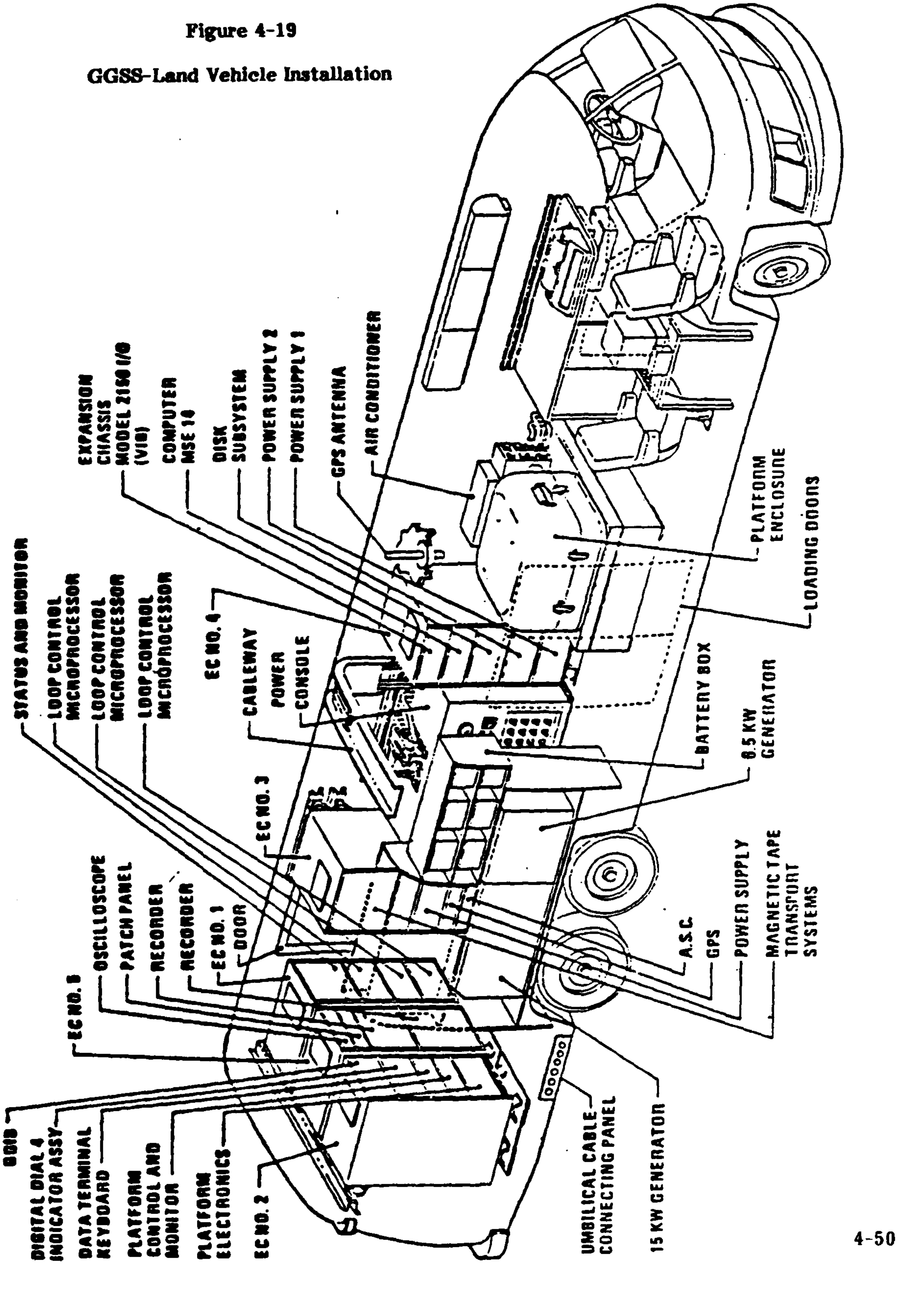


Figure 4-20

Van Interior-Front View

Figure 4-21

Alpha Grapic Video Terminal and Aircraft Display

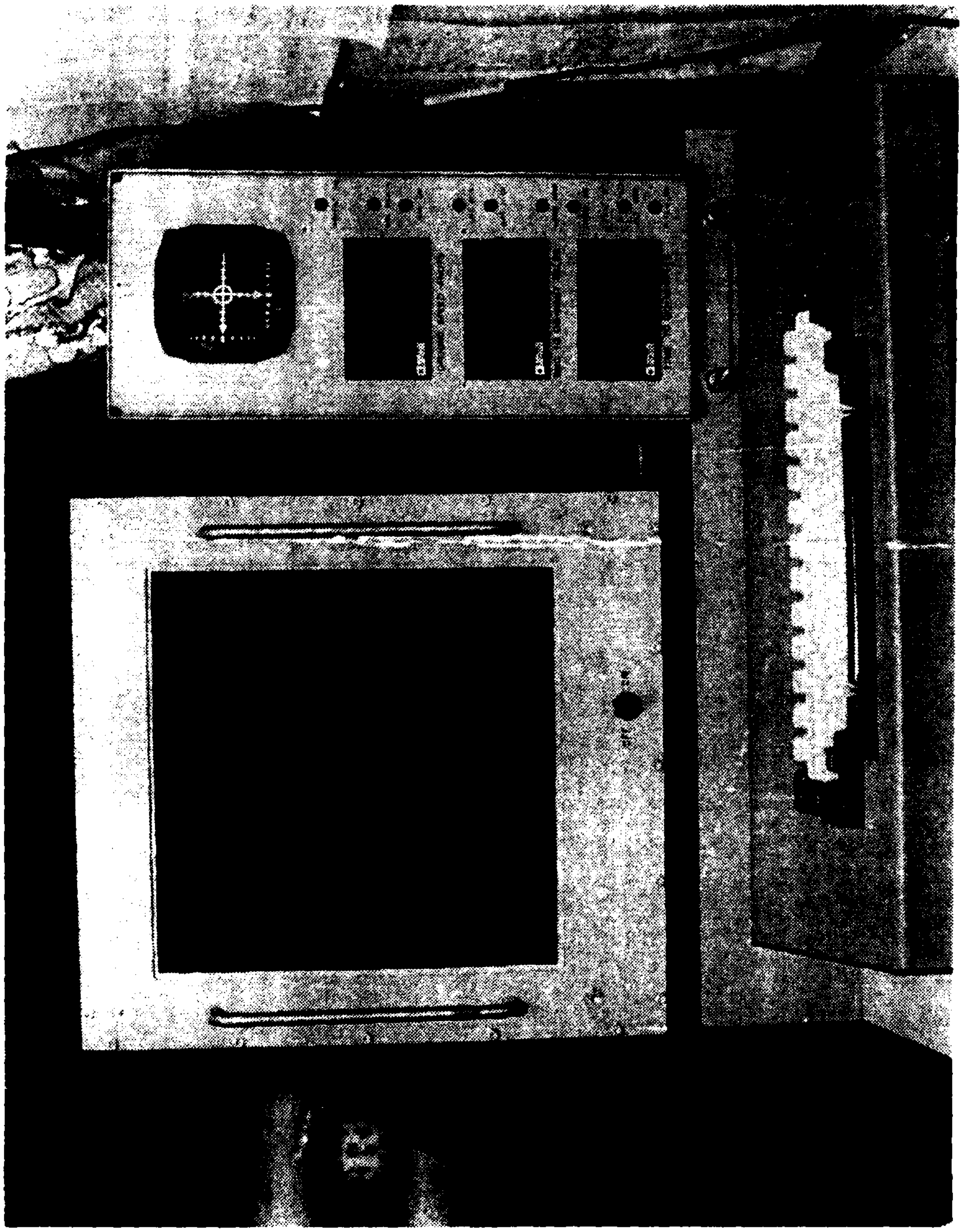


Figure 4-22

Van Interior Rear View

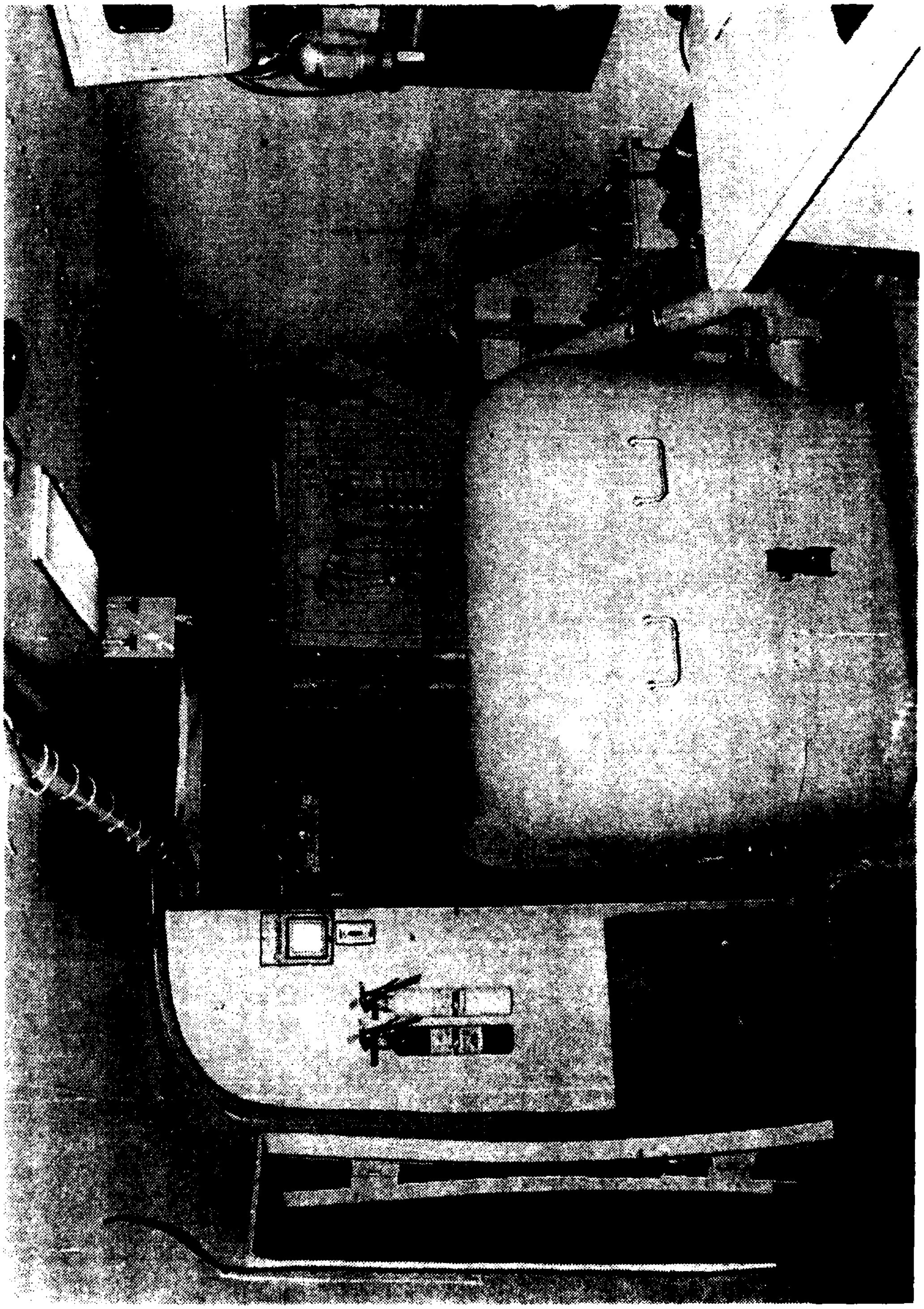


Figure 4-23

Van Side Door View

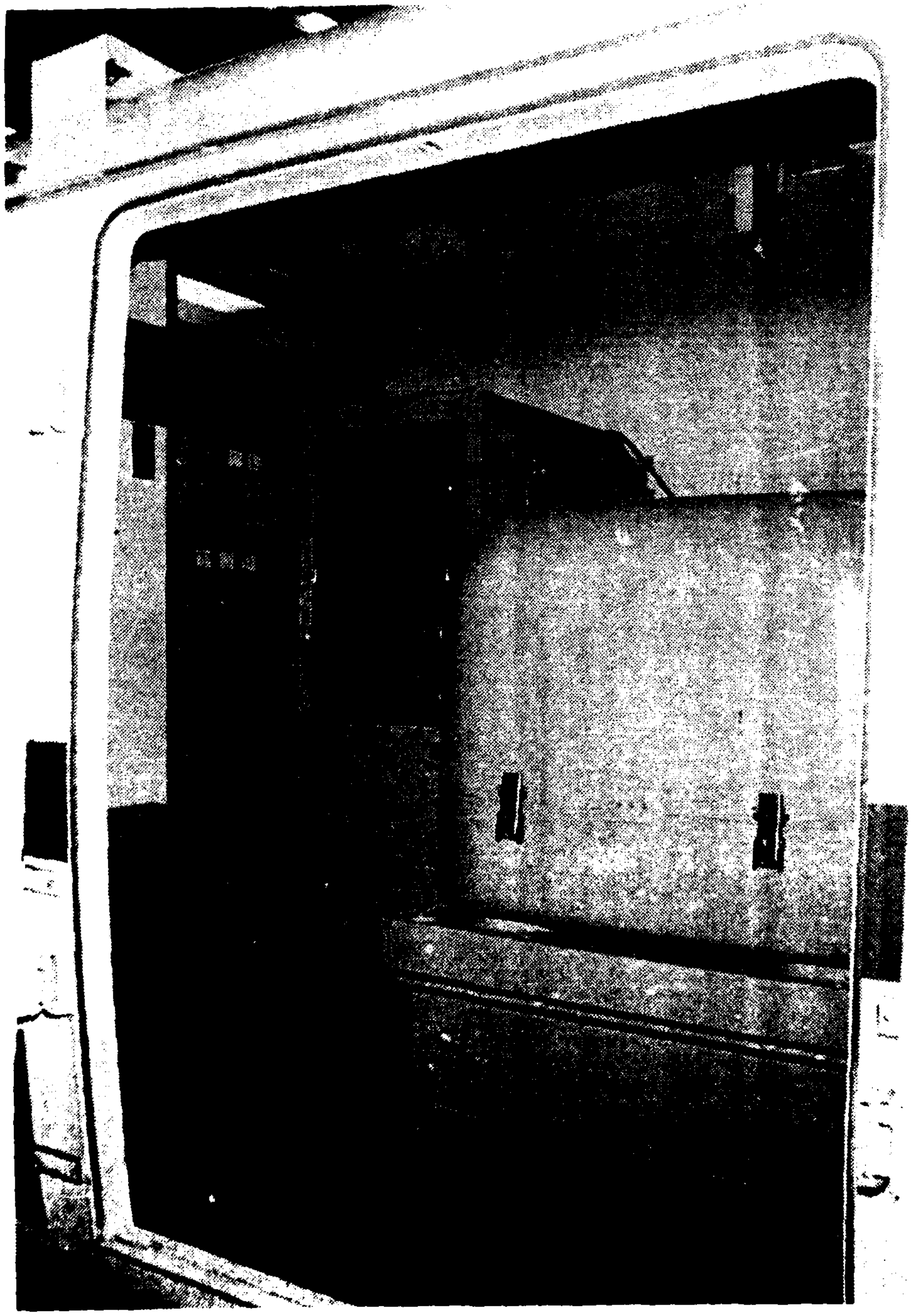
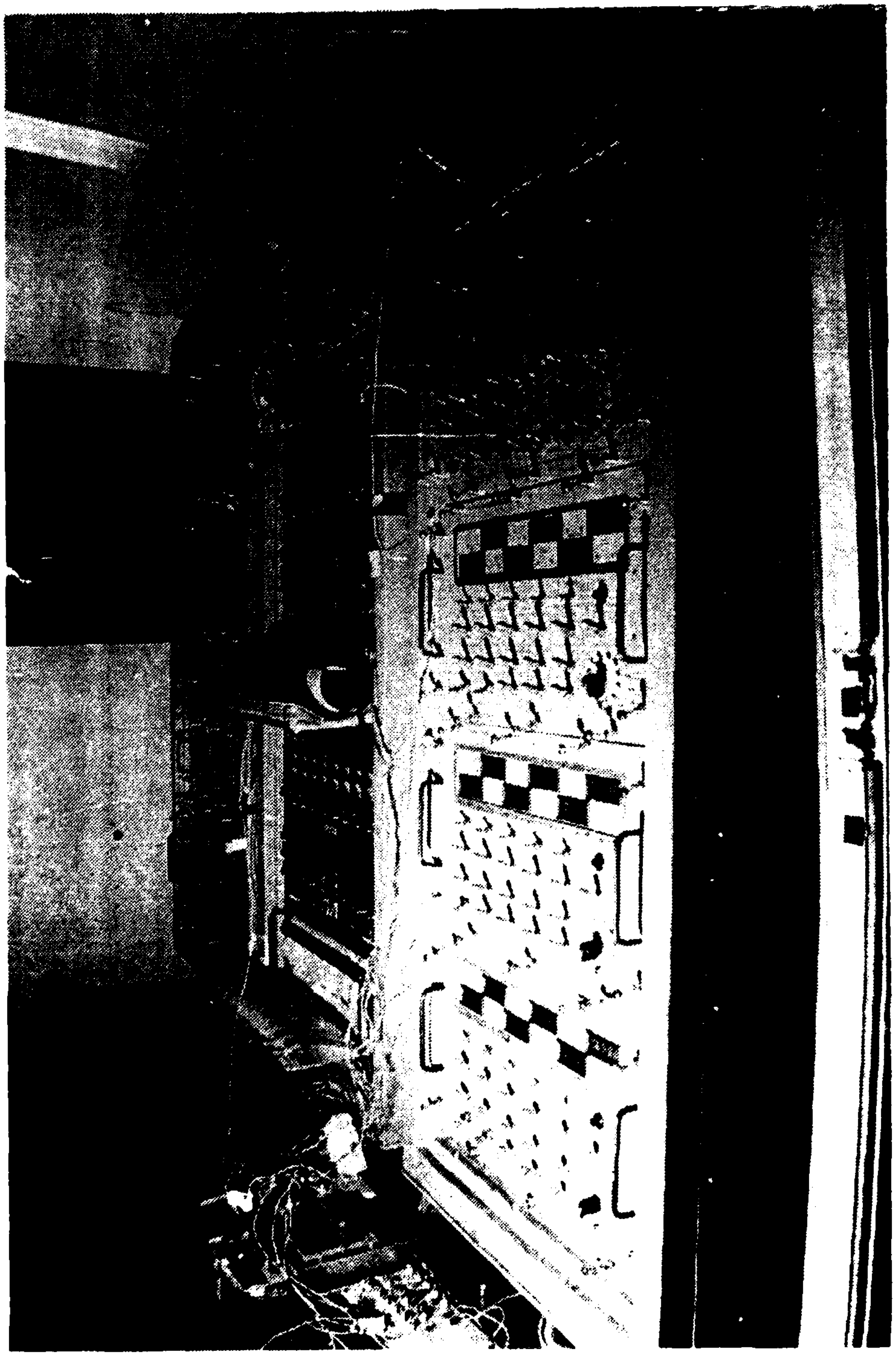


Figure 4-24

Van Interior Rear View



4.4 Van Gradient Calibration

4.4.1 Introduction

The gradients measured by the GGI's include the van's mass distributions about the north pointing and leveled GGSS platform. These must be removed from the total gradient measured to obtain the desired components, namely those due to the earth's field. The van's self gradient, however, varies with the van's pitch, roll and heading. The gradient component in the GGSS measurements which are due to the van must be calibrated in terms of the platforms pitch, roll and azimuth, synchro readings. These relate the van's mass orientations with respect to the platform mounted GGI's.

This calibration was performed inside the high bay area at the east end of the Bell plant in Niagara Falls Blvd, Wheatfield, N.Y. This area is the regular storage site of the land survey vehicle.

The general procedure involved orienting the van at selected headings with respect to north and at each heading tilting the van on both left and right sides. For each heading, then, the average gradient was obtained with the vehicle level, rolled left and rolled right. The heading directions were marked by masking tape strips laid out on the floor at the desired angle with respect to north. Front and rear wheel ramps were made of a height such that when the van was driven to place the front and rear wheels of one side on these ramps, the vehicle was rolled with that side up 3°.

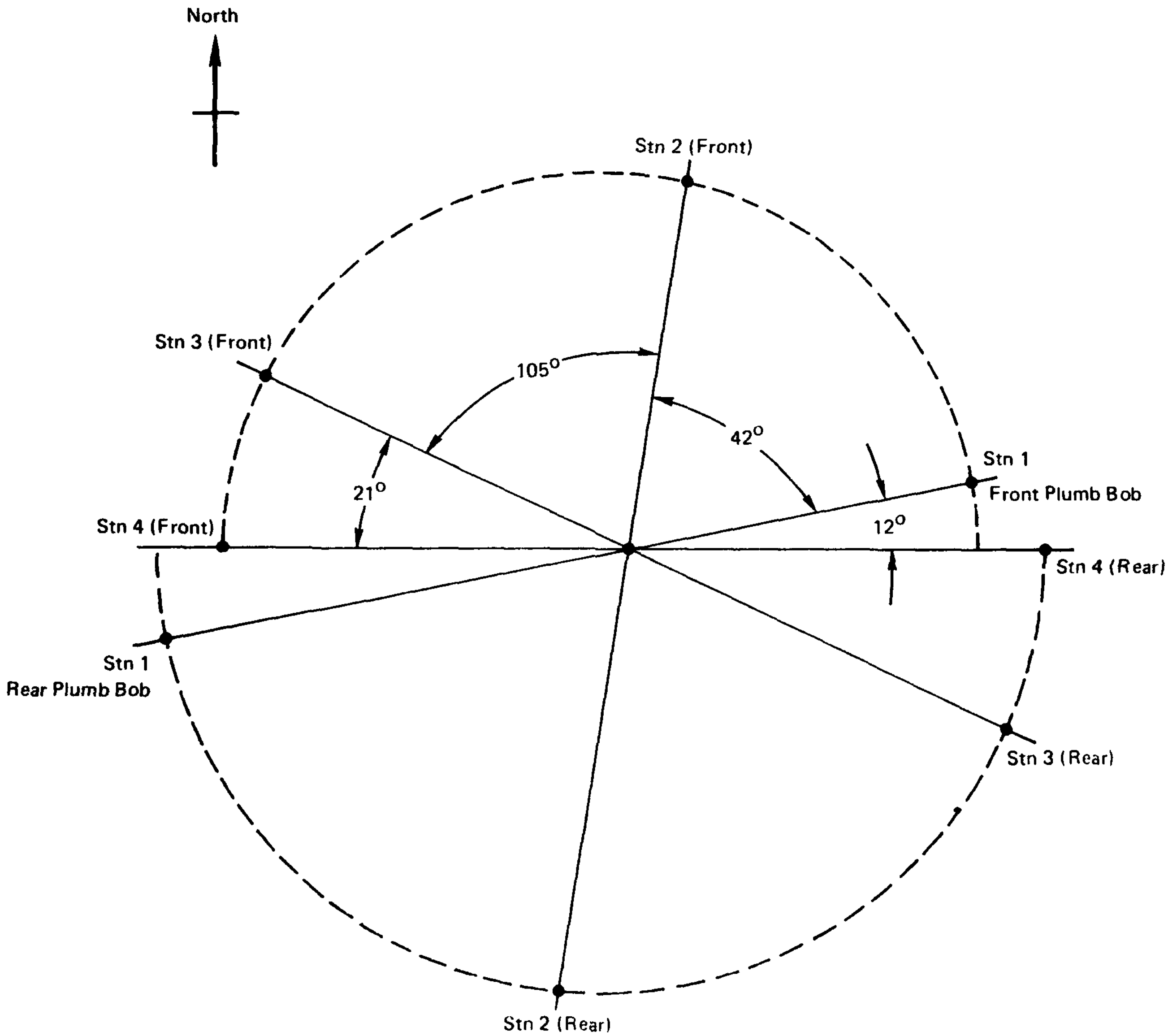
For each of the selected headings a point was marked on each end of the masking tape strip which defined the direction. Plumb bobs were mounted at the centers of the front and rear bumpers. In orienting the van, the vehicle was manuevered until each plumb bob was approximately over the marked point. Because it is quite impractical to jockey the van precisely over these points, particularly when in either of the "van-on-ramps" attitudes, when a reasonable alignment had been achieved, the actual point under the plumb bob was marked on the floor. The idea was to use the actual points to precisely determine the vehicle heading as defined by the centers of the fore-aft plumb bobs.

Figure 4-25 show the nominal headings selected with the target markings for the front and rear plumb bobs. For example, station 4 is an east-west line. When properly positioned the front of the van is facing west and the front and rear plumb bobs are suspended over the points shown as STN4 (front) and STN4 (rear) respectively.

Figure 4-25

Floor Markings

Van Self-Grad Cal



4.4.2 Detailed Procedure

The data acquisition procedure for the van self-gradient calibration follows:

1. Orient van to station #1 heading.

2. Gyro compass (Plat Run B) until stable az. synchro output is achieved.

3. Read az. syncrho on computer video terminal and enter as Ψ_{vp} new value. Note: Ψ_{vp} is the vehicle heading which is entered to align the platform north in Plat Run E which is defined in 4. following.

4. Switch to Plat Run E with 500°/hr. constant carouselling. Note: Plat Run E is the mode which aligns the platfrom by azimuth synchro control and levels the platform with the accelerometers. This mode is here used to attain rapid north alignment.

5. Start tape drive, enter event marker #1, and record all system output data for two carousel revolutions (approx. 1 hr. 26 minutes).

6. During the two carousel revolutions, suspend front and rear plumb bobs to just above floor surface. Also, mark tire footprints to aid ramp positioning for subsequent left and right roll attitude test interval at this azimuth station.

7. While carouselling continues, apply small patch of masking tape to floor just under plumb bobs. When swinging motion has ceased, transfer plumb bob point location to the floor by using a felt tip pen to mark the tape. Transfer point to ± 1/8 inch accuracy.

8. When two carousel revolutions are complete, enter event marker #2. End recording.

9. Back up van maintaining approximate heading alignment to station markings on floor. Position tire ramps to elevate van on driver side. Drive van forward onto ramps to bring plumb bob locations approximately to same position as previously on floor (within 2 or 3 inches).

10. Repeat steps 5 thru 8, installing new mag tape and indexing event marker as required. Then repeat again for van elevation on passenger side. Sequenced the dates for A level, B van driver, C van passenger.

11. Prepere van for repositiong to Station 2 by typing in a new Ψ_{vp} value ($\Delta\Psi_{vp}$ will be 42° (±?)). Do not hit "ENTER" key for new Ψ_{vp} value until van engine is started and reposition just begins.

12. Repeat steps 5 thru 11 for stations 2, 3 and 4. The $\Delta\Psi_{vp}$ between stations 2 and 3 shall be 105° and between 3 and 4 shall be 21°.

4.4.3 Results

The actual plumb bob positions were designated at each position by A for van level, B for van rolled 3° with drivers side up and C for van rolled 3° with driver side down. After the calibration were completed the displacements of the actual position were measured from the nominals of Figure 4-25. Table 4-8 shows the corrected headings based on the actuals.

Table 4-8 Corrected Heading for Self-Gradient Calibrations

A=Van level, B=3° drivers side up roll, C=3° drivers side down roll

Station No.	Roll	Azimuth Angle (Degrees)
1	A	0.00°-Baselne
1	B	0.27
1	C	0.14
2	A	41.78
2	B	41.91
2	C	41.51
3	A	146.96
3	B	147.10
3	C	146.81
4	A	168.08
4	B	168.12
4	C	167.72

The algorithms used to separate the van self-gradients from the earth's field are patterned after those used for the Navy Gravity Sensors System Program. These are described in depth in Bell Aerospace Report No. 6501-927079.

The results of the van self-gradient calibration are discussed in Section 6.0 Land Mobile Gravity Survey.

4.5 Aircraft Installation

4.5.1 General Approach

The REVCON Motor Coach with the GGSS and equipments installed as described in Section 4.3 is a self-contained mobile system. The GGSS is tranformed into an airborne survey system by driving the REVCON Coach onto a C-130 Hercules aircraft that has been prepared with an umbilical cable which connects to the coach. The cable supplies power to the coach (and GGSS) as well as signal and communications links between the GGSS and aircraft. The coach is mechanically secured inside the aircraft by chains that attach from chassis-mounted shackles under the coach to a standard array of tie-down rings on the cargo compartment floor of the C-130.

Figure 4-26 is the composite sketch of the GGSS vehicle on the loading ramps entering the C130 and fully inserted in the C130. Figure 4-27 is a photograph of the van partially inside the C130. Figure 4-28 is a rear view of the C130 with the van fully inserted prior to closing the aircraft rear loading hatch. The loading ramps for driving the van into the aircraft and the aircraft's rear loading hatch can be seen clearly in these photographs.

4.5.2 Detailed Description

Melard International Service Center of Miami, Florida modified the Southern Air Transport C130 in the spring of 1986. These modifications consisted of the installation of cabling, junction boxes and components in three main areas.

- Distribution of public utility or aircraft power to the van for GGSS power, van airconditioner and van lighting.
- Bell provided displays and controls for pilot monitoring and mode selections during GGSS airborne survey.
- Smith Industries fuel quantity system.

Additional changes involved the GPS antenna and an auxillary barometric altimeter. The GPS antenna was installed on the upper side of the aircraft fuselege. A removable coaxial cable was installed which connected this antenna to the van at the location of the now removed van antenna. The auxiliary barometric altimeter was installed to provide this altitude information directly to the GGSS system. The aircraft barometer was not used in accordance with the philosphy of minimum disturbance or modification of existing aircraft systems. This independent barometric atimeter is designated as BAR02.

Figure 4-29 shows the power block diagram of the airborn system. The van components are described in Section 4.3. The additional major components shown added to the C130's existing system are:

- 2 DC/AC 15 KVA inverters
- 2 400 Hz T/R units
- 2 50 Hz T/R units
- 2 remote control circuit breakers
- 4 DPDT relays
- 1 power transformer

Figure 4-26

C130 Installation

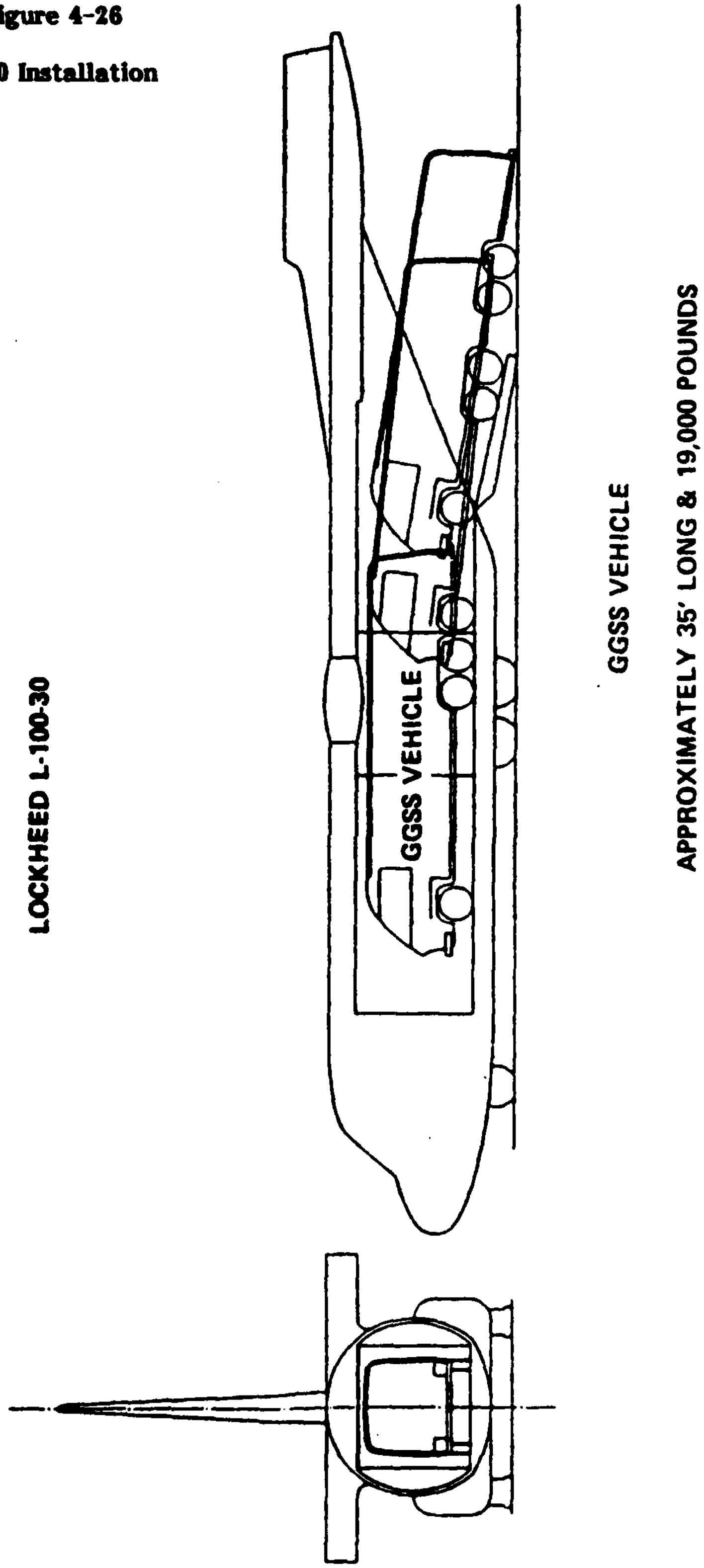


Figure 4-27

Van Entering C130

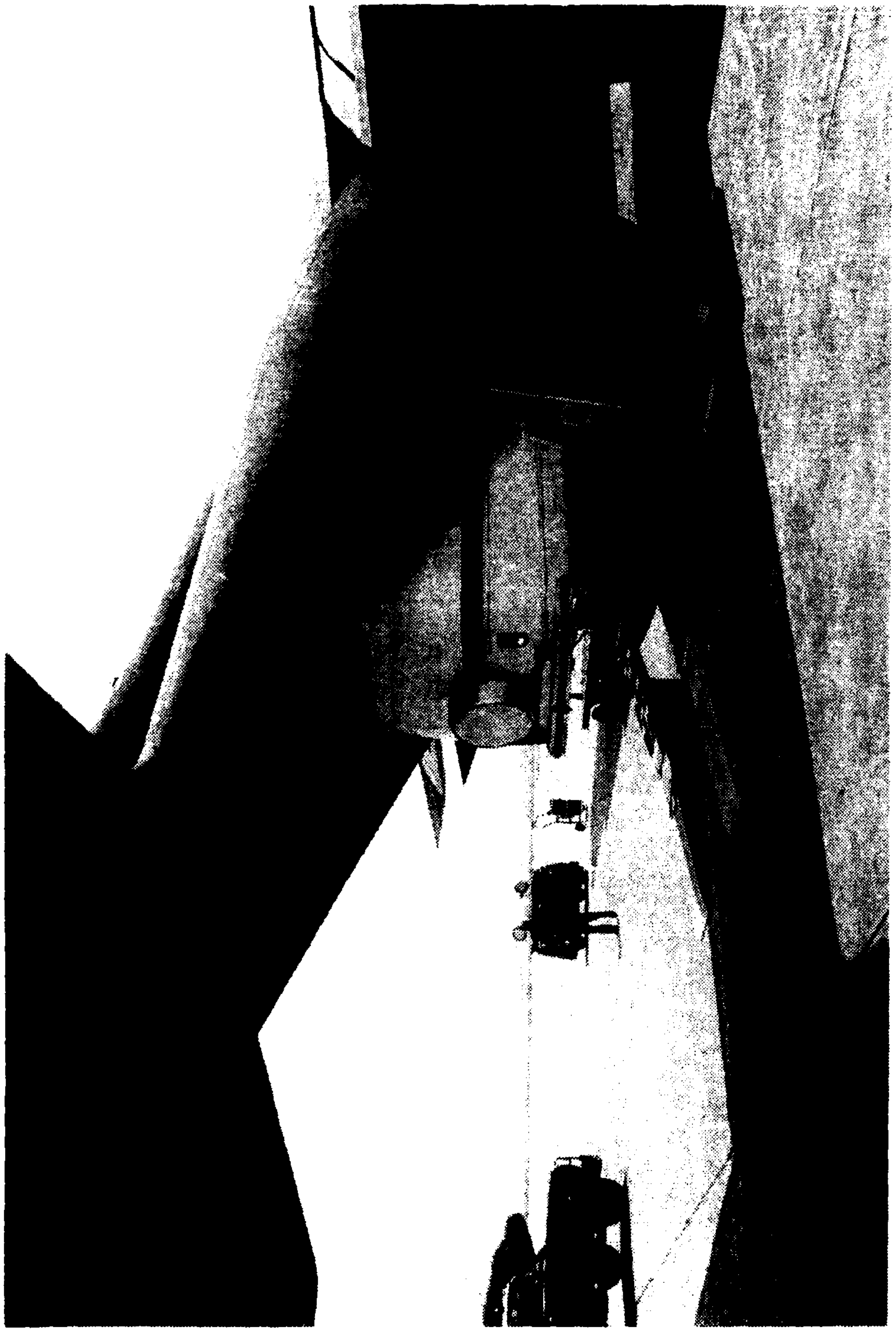


Figure 4-28

Rear View Van Aboard C130

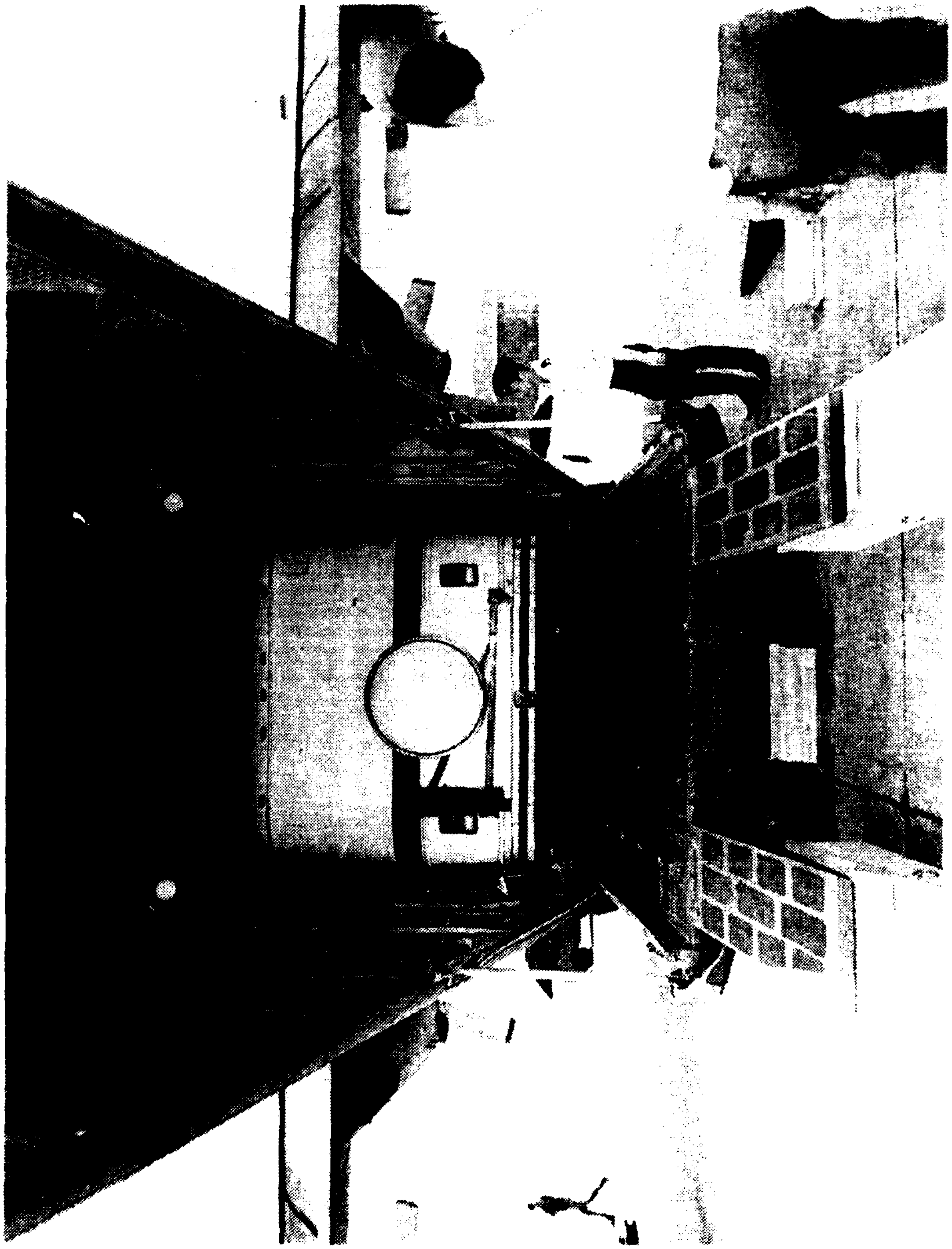


Figure 4-30 depicts in block diagram from the GGSS/C130 signal interface wiring. In this figure, the filled in circles shown on the cable interconnects designate the connectors which link the aircraft and van segments of the GGSS airborne system. Going from left to right in this figure the ROLM MSE/14 computer is shown. The various data converters process signals between the GGSS System and the other systems. The processing is analog to digital (A/D), digital to analog (D/A), digital to digital reformatted (D/D) and discretes generation. The designation VIB on rack 4 stands for Vehicle Interface Buffer and is the Expansion Box of the ROLM System.

The van internal connection shown between racks 3 and 4 is a preparatory function before sending signals out to the aircraft. The analog and discrete signals from the VIB in rack 4 are processed by the ASC (Aircraft Signal Conditioner) drawer in rack 3. The ASC scales and formats (example: DC signal from VIB to modulated 400 CPS for C130 autopilot control) information for acceptance by the C130 systems.

Leaving the van from the ASC drawer are the signals for the pilots instrument panel and controls. The GGSS displays are identical with those shown in Figure 4-21. The van systems in Figure 4-21 are in parallel with their counterpart in the cockpit. The GGSS operator in the van and the pilot monitor identical functions. Also shown enlarged in Figure 4-30 are details of the 4 alternate, dual lamps split-face pushbuttons on the panel labeled GGSS CONT. These signal the pilot as to the status of the platform navigation function, whether or not GPS has been selected and whether the autopilot's pitch and roll axes have been engaged. These axes may be engaged separately or together.

Figure 4-31 shows the Smith Industries Fuel Quantity System in block diagram form. Its importance to the GGSS program is due to the precise measurement of fuels state. The aircraft self-gradient varies as fuel is consumed from full to empty during flight. As shown in Figure 4-30, this fuel state is transmitted in digital format to the GGSS system. Modeling enables self-gradient adjustments required by the changes in fuel mass and distribution.

Figure 4-29

Power Block Diagram Airborne System

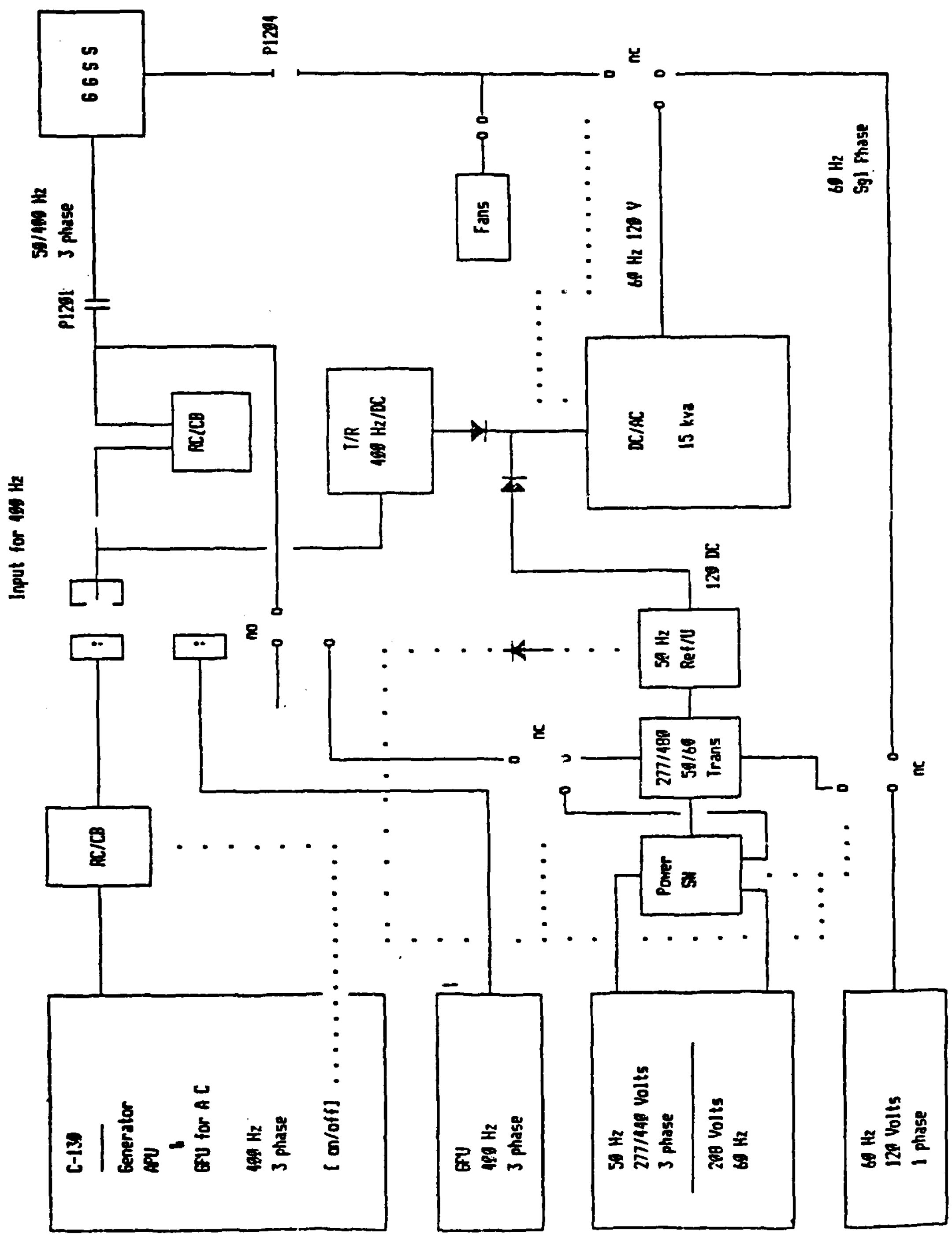


Figure 4-30

GGSS/C130 Signal Interface-Controls and Displays

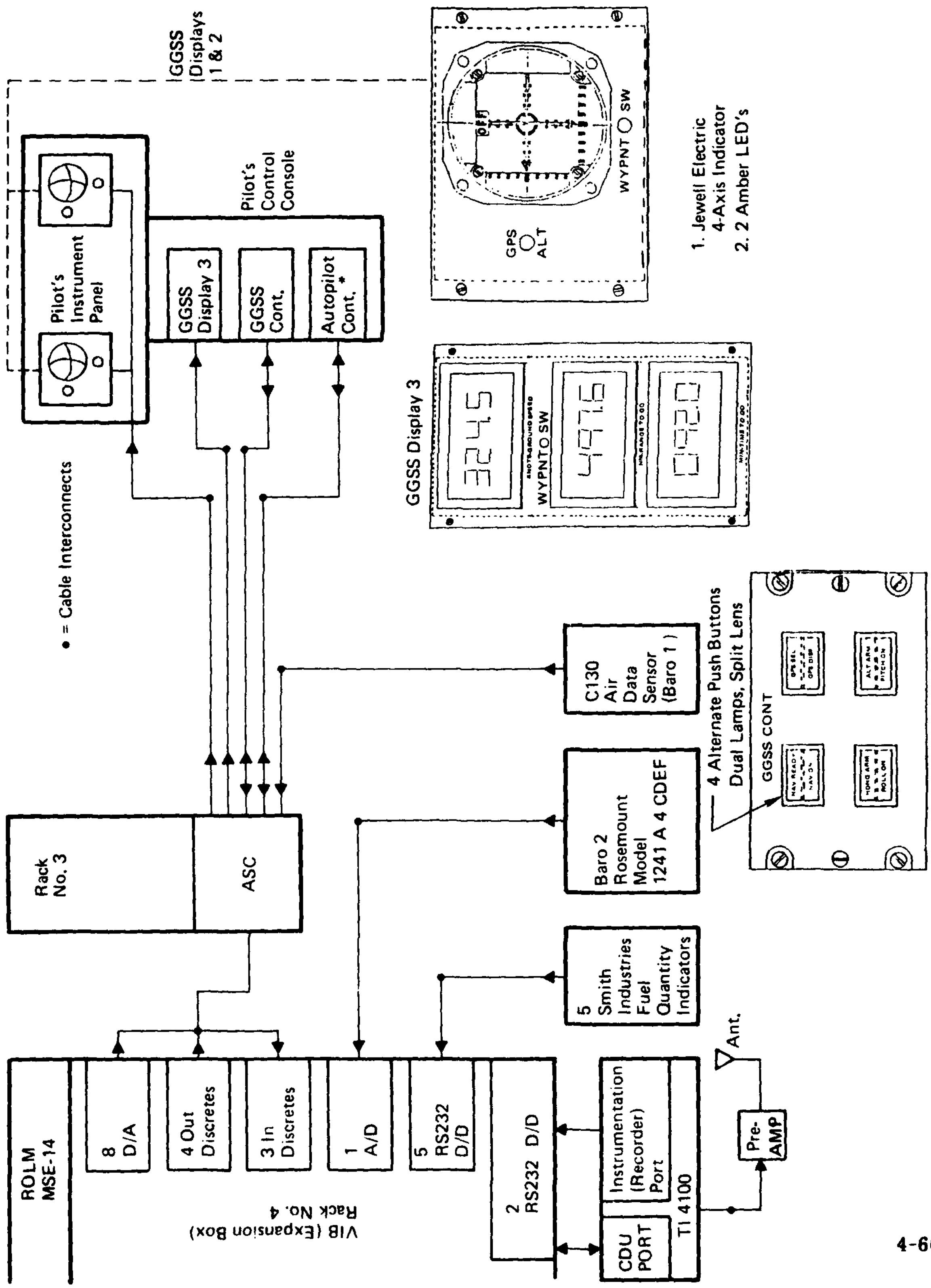
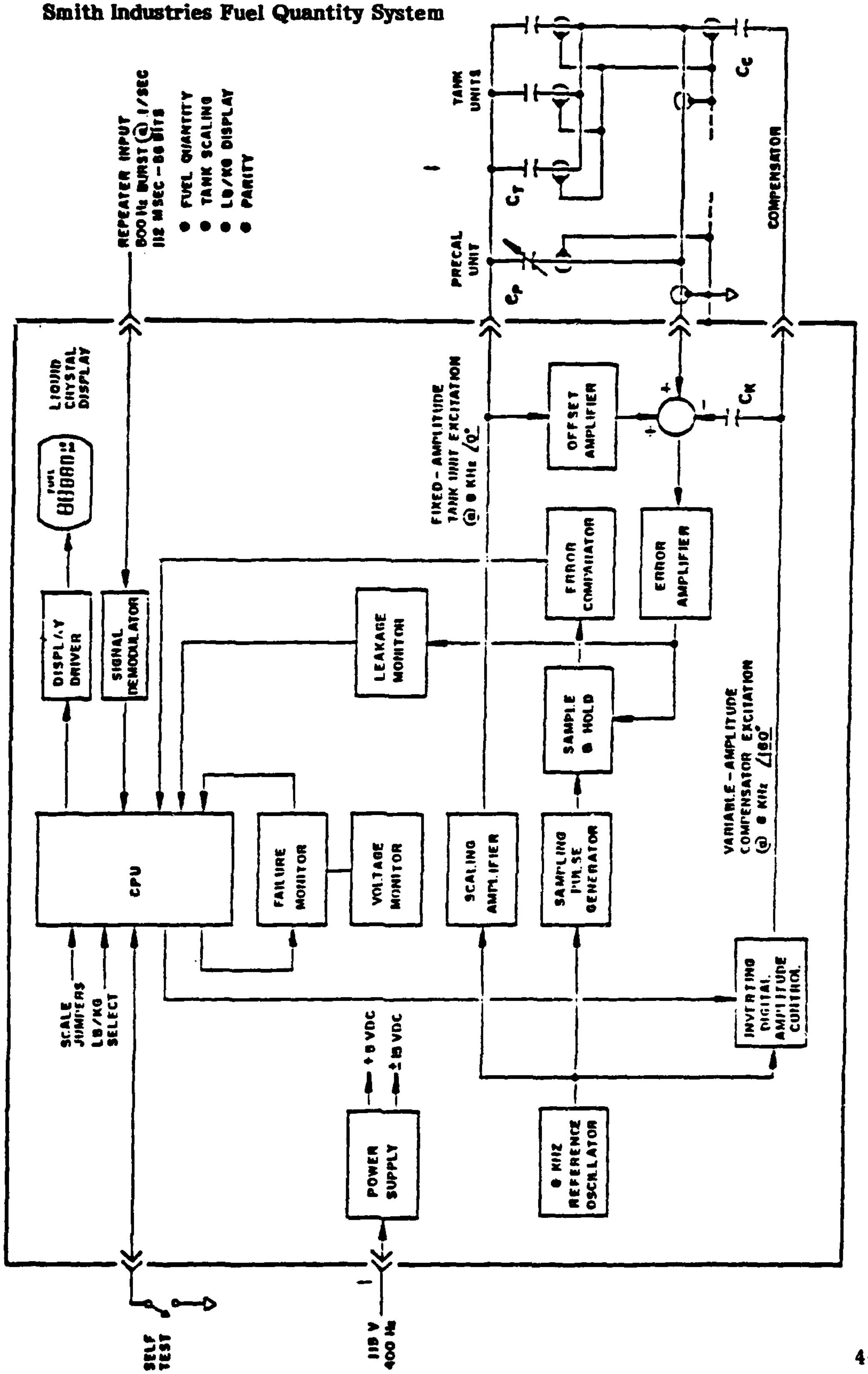


Figure 4-31

Smith Industries Fuel Quantity System



4.6 Aircraft Gradient Calibration

4.6.1 Introduction

The need to know the van self-gradient was discussed in Section 4.4.1. For airborne gravity surveys the van is shackled in the cargo bay of the C130. For these surveys, the self gradient of the aircraft must also be known. In this context the van is essentially part of the aircraft. The gradient components which are due to the mass distributions of aircraft structure, engines and fixed on-board equipments including the van itself must be calibrated. Again the three platform angles as read by the pitch, roll and gyro synchros are the independent variables in the self-gradient field model. Once calibrated the gradients measured at an aircraft attitude as identified by these angles can be corrected by subtracting the modeled field leaving the desired component due to the earth's field.

The aircraft self-gradient calibration was performed in December 1986 at the aircraft parking ramp between the Bell Aerospace plant and the Niagara Falls International Airport. Surveyed lines were painted on the concrete apron to establish known heading directions. These were the radii of a circle with position 1 being oriented north-south. The other radii were layed out in 30° steps, encompassing 360°.

The aircraft was jockeyed into position by a ground tug at each of these headings. Figure 4-32 is a photograph of the operation. At each heading, the aircraft was pitched up in 3° increments to a maximun of 9° pitch up from the "wheels on ground" position. This was accomplished by using a mobile construction crane which fastened on the hard lifting points just below and aft of the cockpit area. This is shown in Figure 4-33. Figure 4-33 is a closeup of one of the lifts which shows the mobile lifting crane up on its pads, braced for the lift. For each attitude the gradients were data logged by the ROLM's magnetic tapedrive for off-line processing to obtain vehicle (van plus aircraft) gradients as function of the platform measured aircraft attitude angles.

4.6.2 Detailed Procedure

The data acquistion procedure for the aircraft self-gradient calbration follows:

1. Park the aircraft along the north-south stripe painted on the ramps apron.

2. In Plat Run E set Ψ_{vp} to 0°. In this mode of platform control, the platform is leveled by the accelerometers and the heading controlled by synchro caging of the azimuth axis. Ψ_{vp} is the assumed vehicle heading with respect to north. By operator entry of Ψ_{vp} equal to the heading of the painted stripe, the platform retains a true north orientation for each aircraft position.

3. When the transients of motion died down as indicated by observing the strip chart recording of the X, Y and Z axis gyro torque commands, begin data logging the six gradients and the platforms pitch, roll and azimuth synchro readings. Continue for ten minutes.

4. Read the platforms pitch synchro. Call this θco.

5. Lift the aircraft's nose up until the pitch synchro reads $\theta co + 3°$.

6. Repeat steps 3 through 5.

7. After each completion of steps 3 to 5, lift the aircraft nose up an additional 3°. Continue until a complete set of pitch up attitudes has been processed. A complete set is: pitch = $\theta co + k3°$, k= 0, 1,2, 3.

8. After completing the k=3 step in 7, enter the heading Ψ_{vp}=30°.

9. Lower the aircraft to its "wheels on ground" position and move the aircraft in aligment with the "30° from north" stripe on the apron.

10. Repeat steps 3 through 9. Continue until a full set of headings have been attained.

    A full set of headings is:

    Aircraft heading from north = k30°, k=0,..., 11. At each new heading, Ψ_{vp} is entered as the value of the new heading.

4.6.3 Results

The data logged gradients were averaged off-line and tagged with the three platform synchro readings. Off-line algorithms identified a set of coefficient which related the aircraft gradient to the platform synchro angle readings. These algorithms strip away the earth's field leaving the gradient components as functions of aircraft attitude. In aerial gravity surveys, the aircraft gradients are subtracted from the gradient measurements leaving the desired earth's field values. Figures 4-35 to 4-47 depict the results.

Figure 4-32

C130 Towed Into Headings for Calibration

Figure 4-33

C130 Nose Lift

Figure 4-34

C130 Nose Lift Closeups

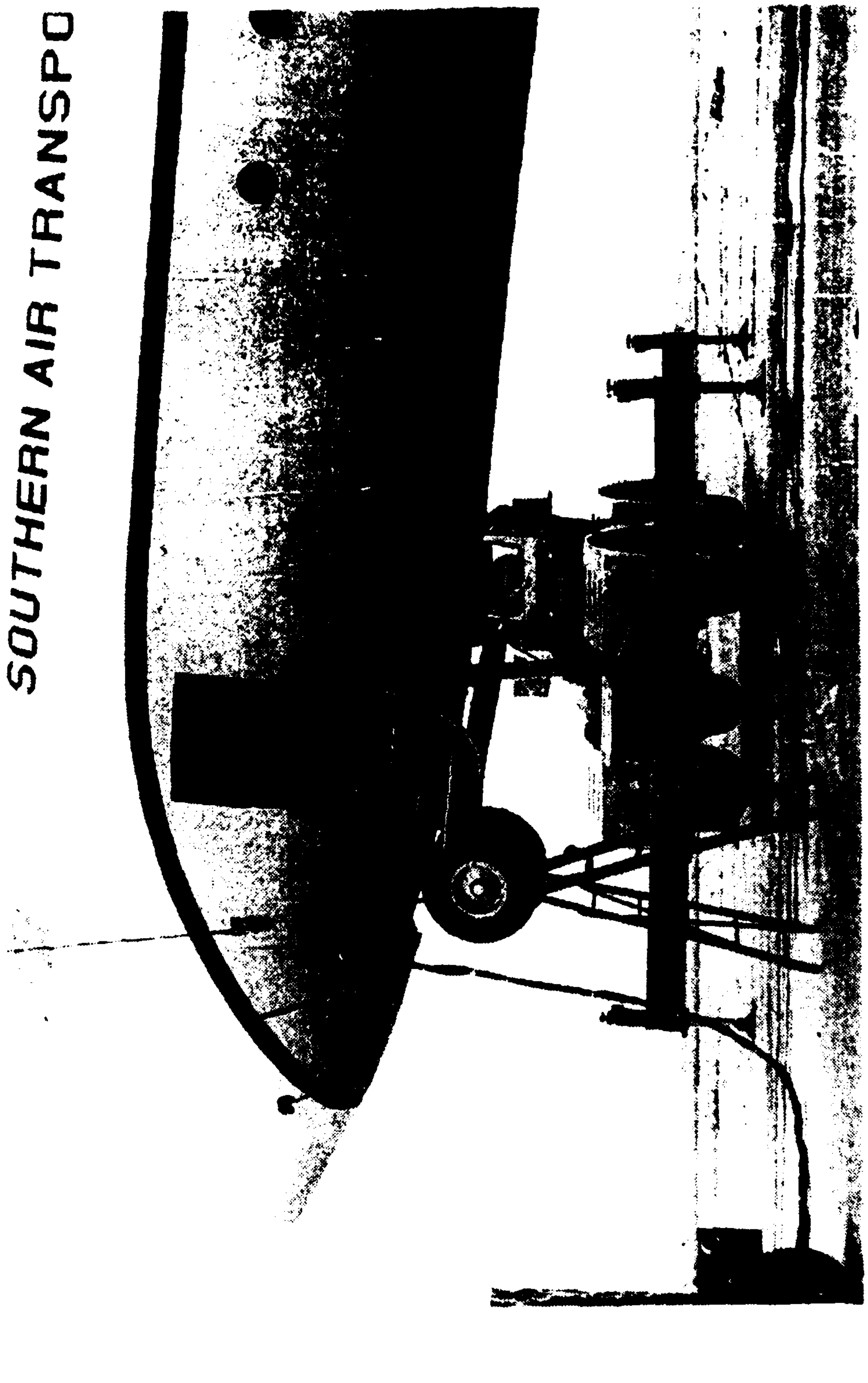


Figure 4-35

Inline 1 Total Self Gradient Compensation Roll -8 +8

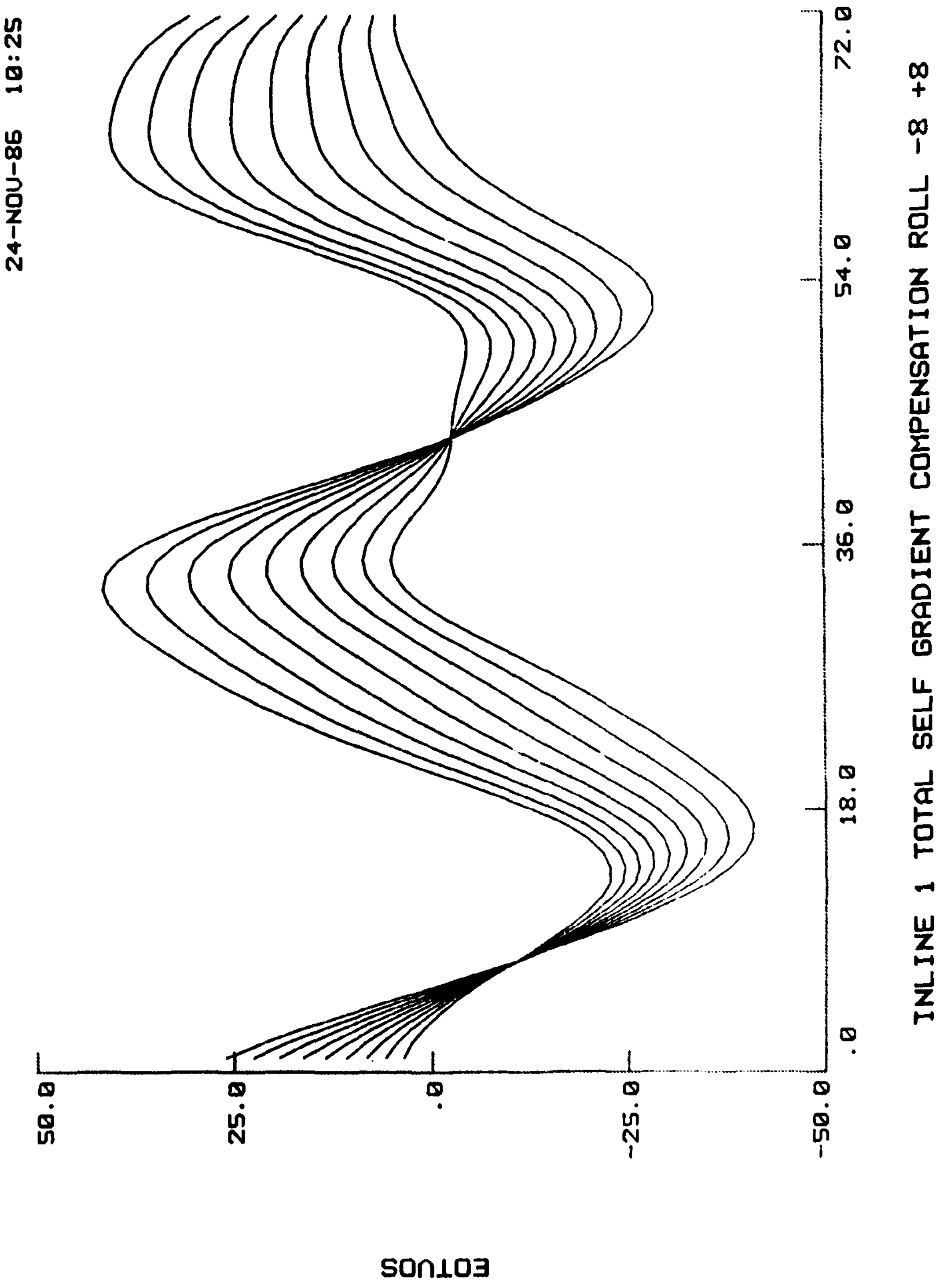


Figure 4-36

Inline 2 Total Self Gradient Compensation Roll -8 +8

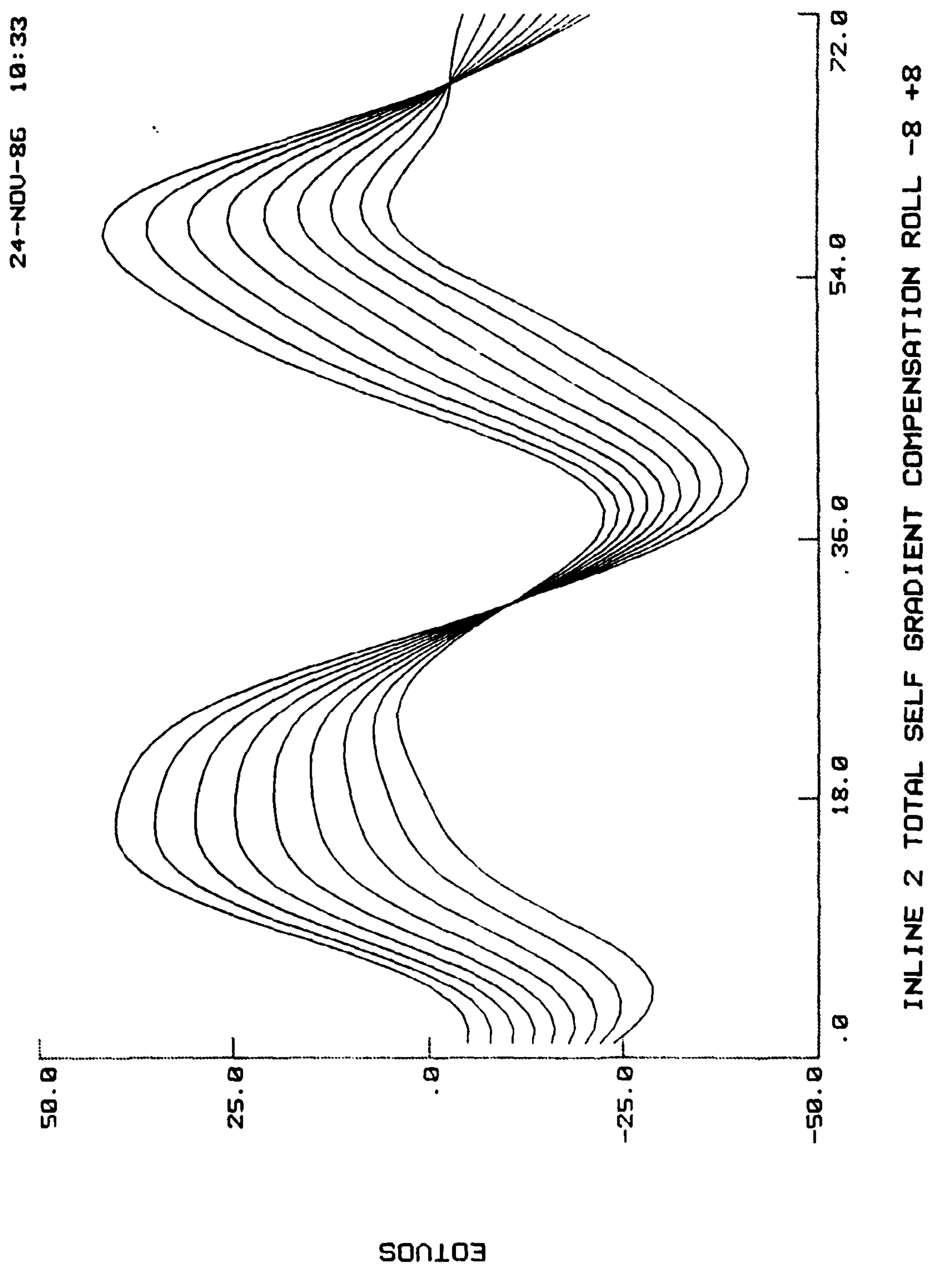


Figure 4-37

Inline 3 Total Self Gradient Compensation Roll -8 +8

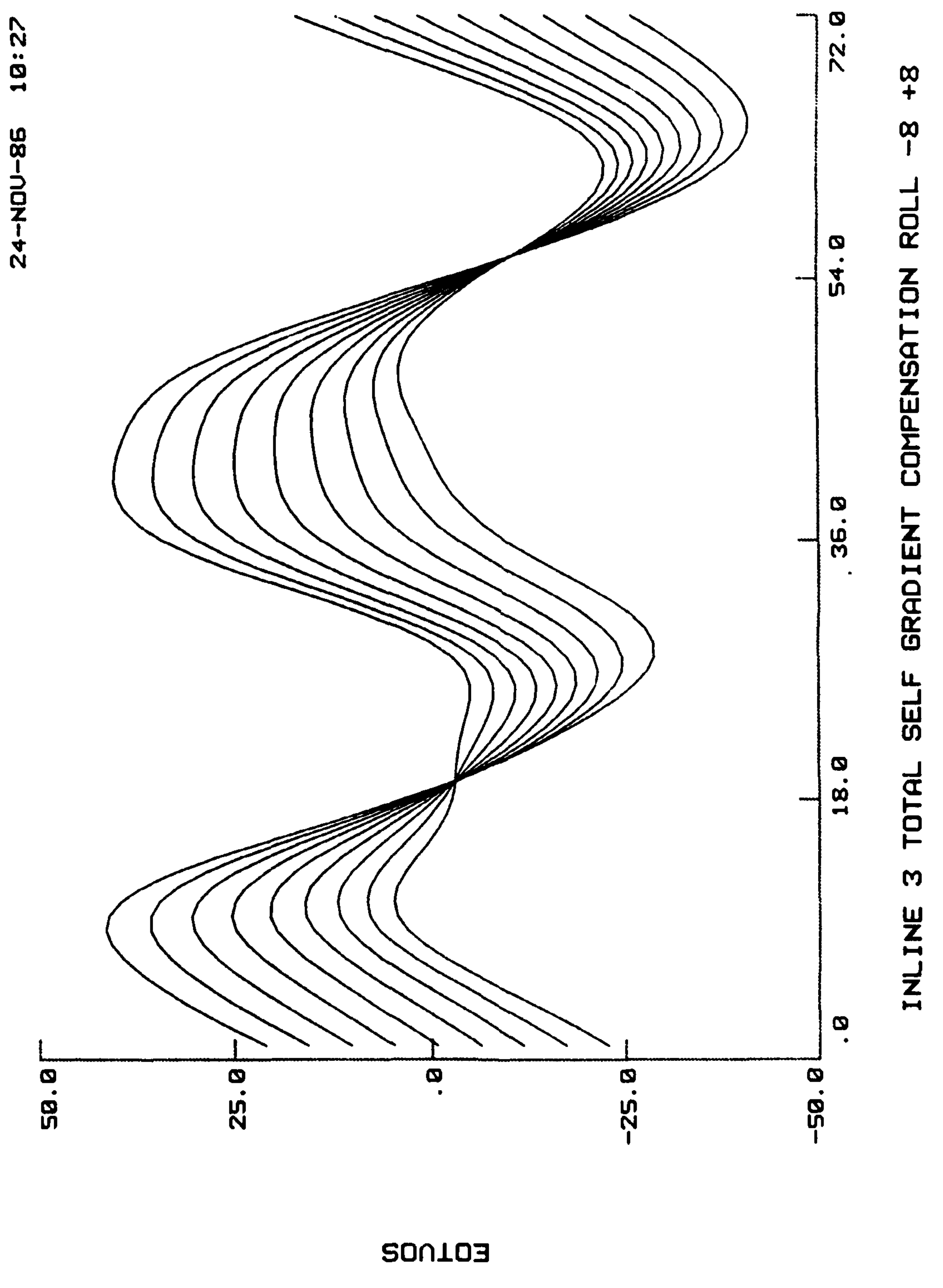


Figure 4-38

Cross 1 Total Self Gradient Compensation Roll -8 +8

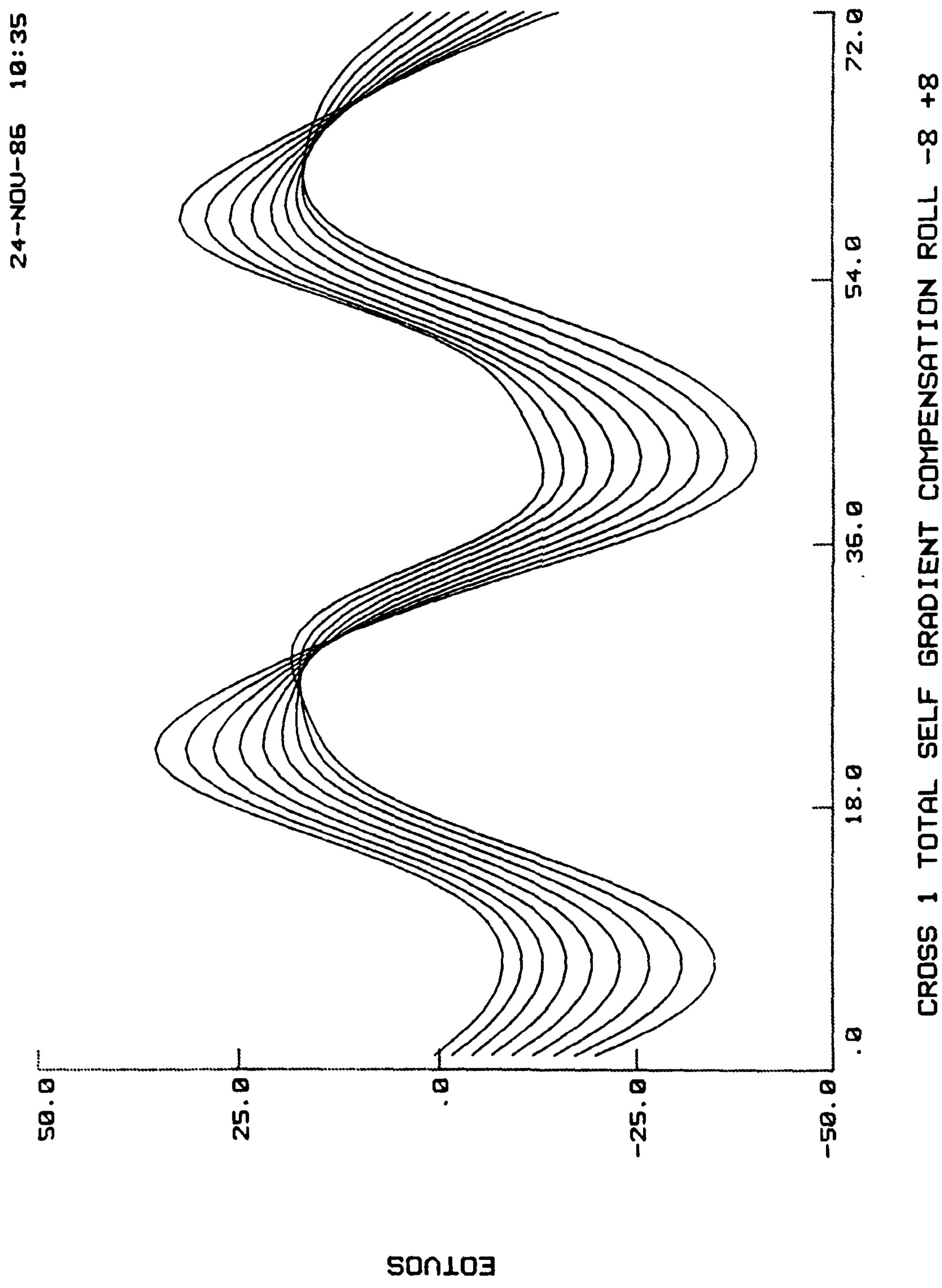


Figure 4-39

Cross 2 Total Self Gradient Compensation Roll -8 +8

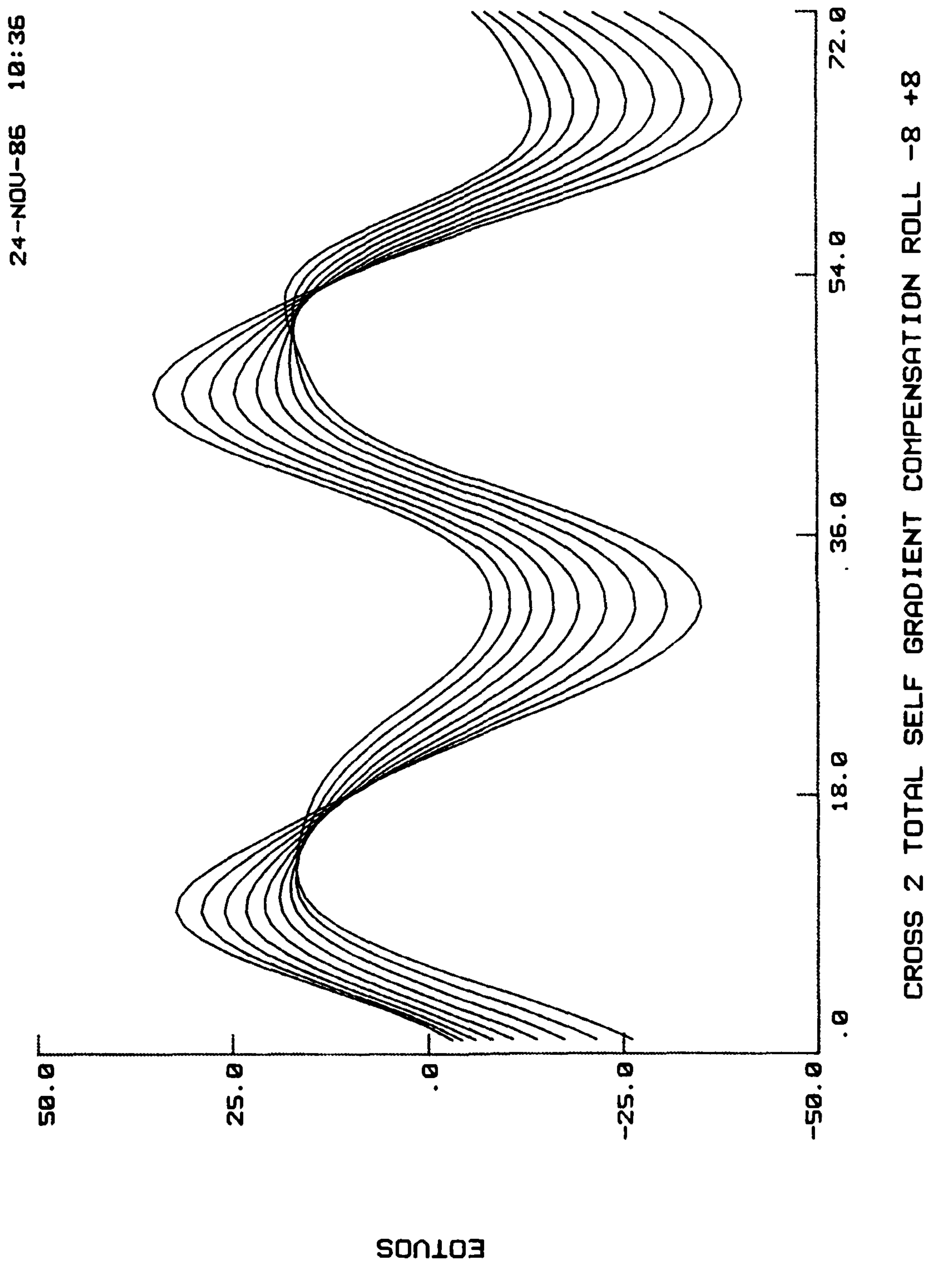


Figure 4-40

Cross 3 Total Self Gradient Compensation Roll -8 +8

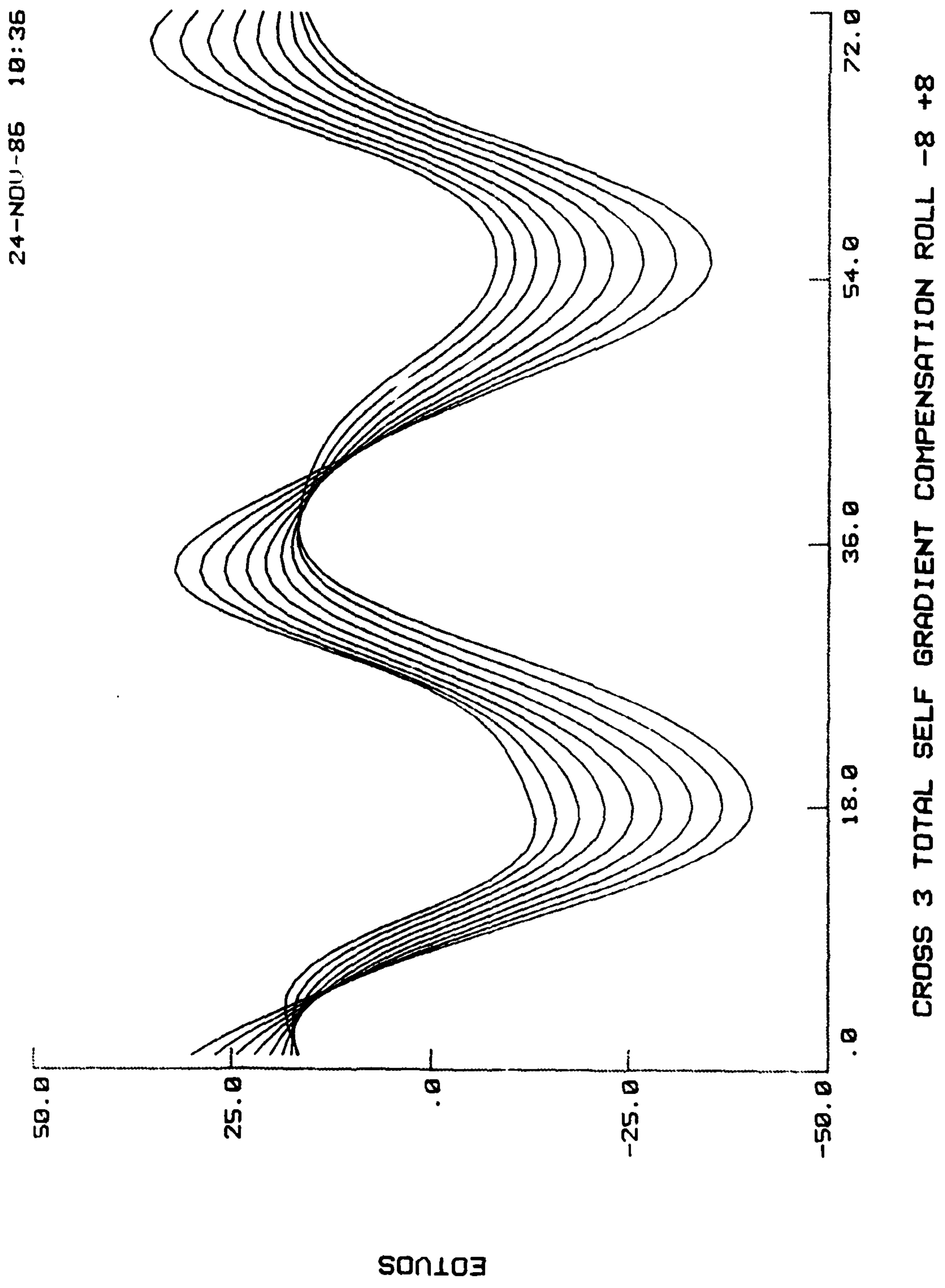


Figure 4-41

Inline 1 Total Self Gradient Compensation Pitch -8 +8

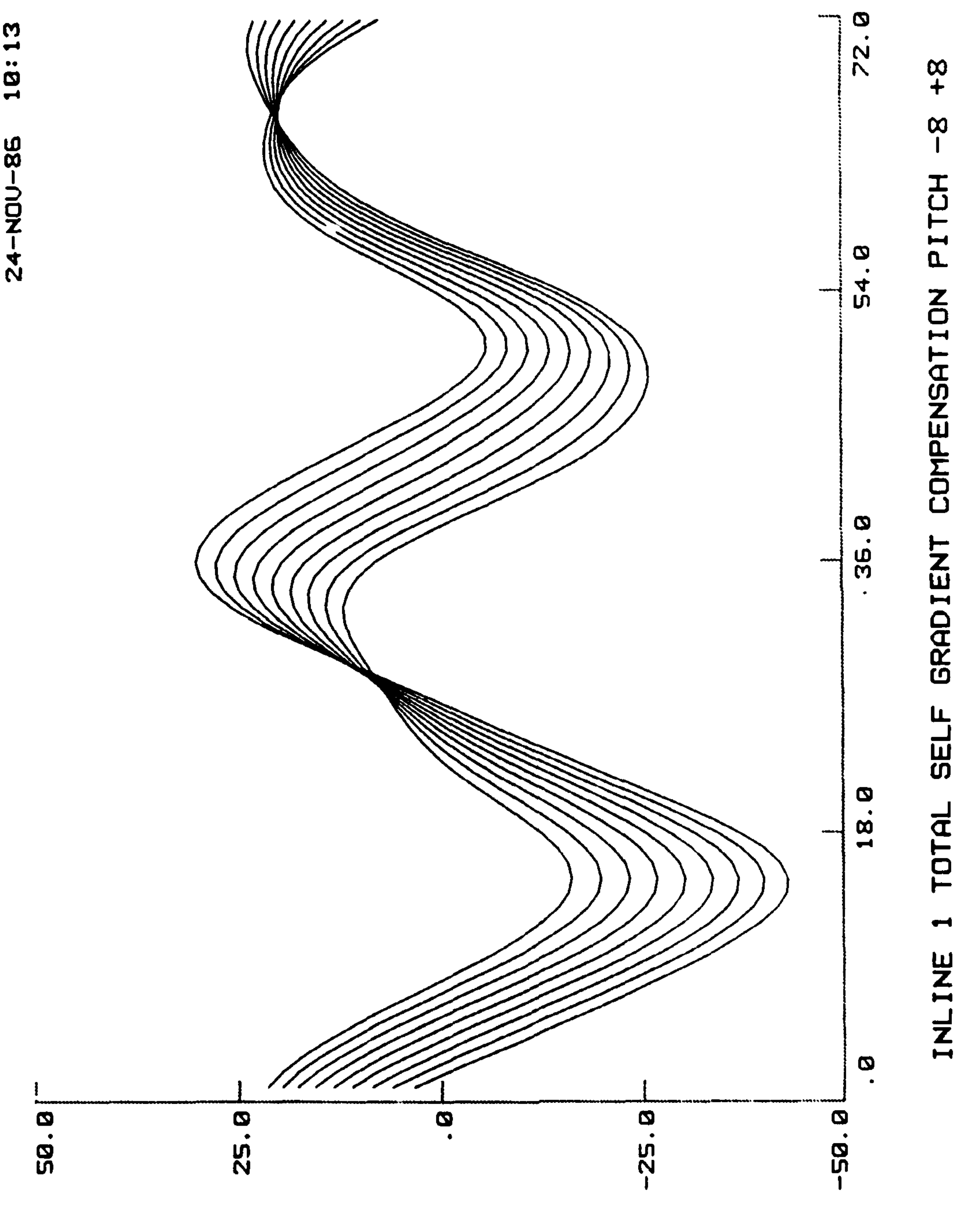


Figure 4-42

Inline 2 Total Self Gradient Compensation Pitch -8 +8

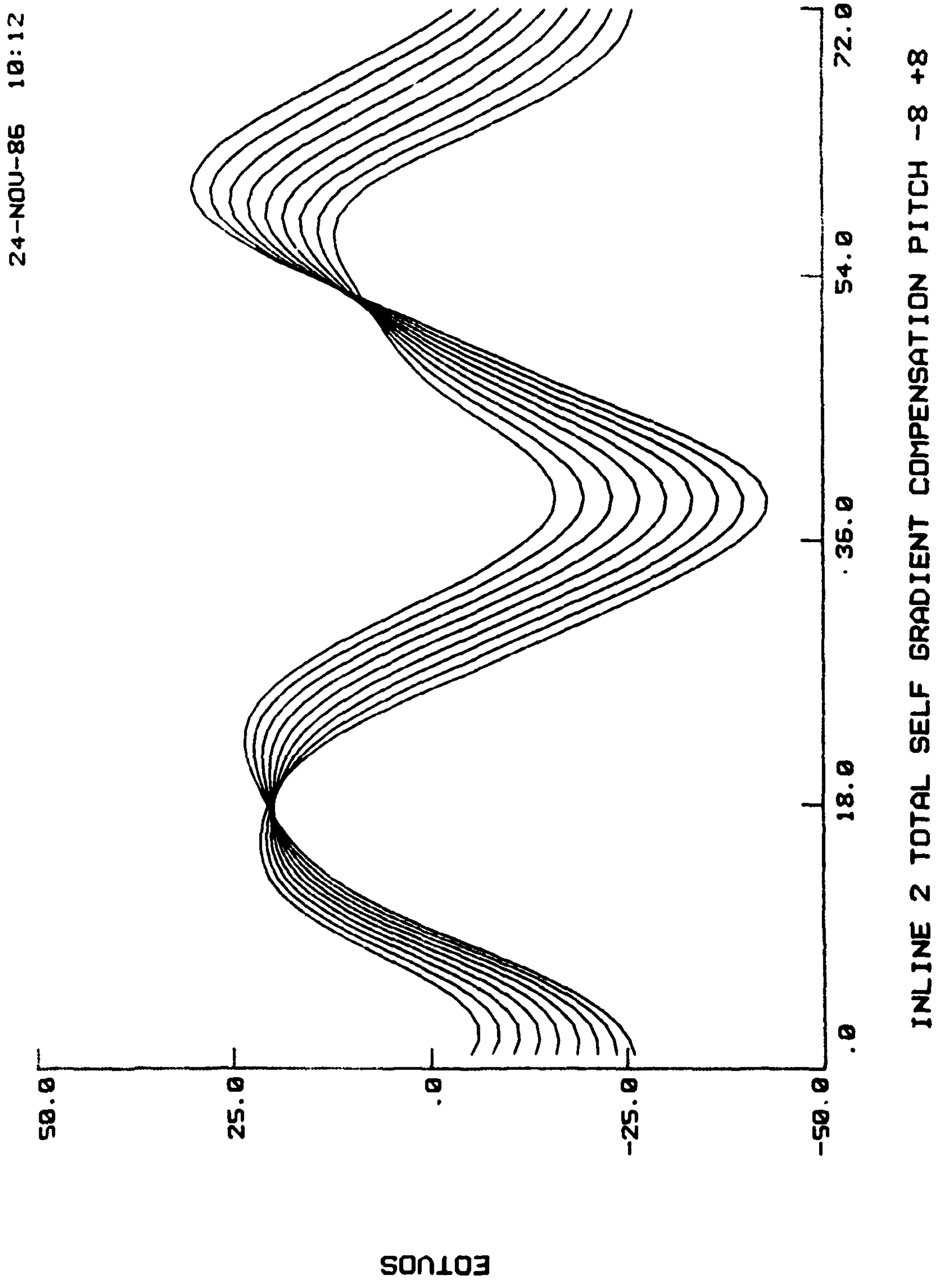


Figure 4-43

Inline 3 Total Self Gradient Compensation Pitch -8 +8

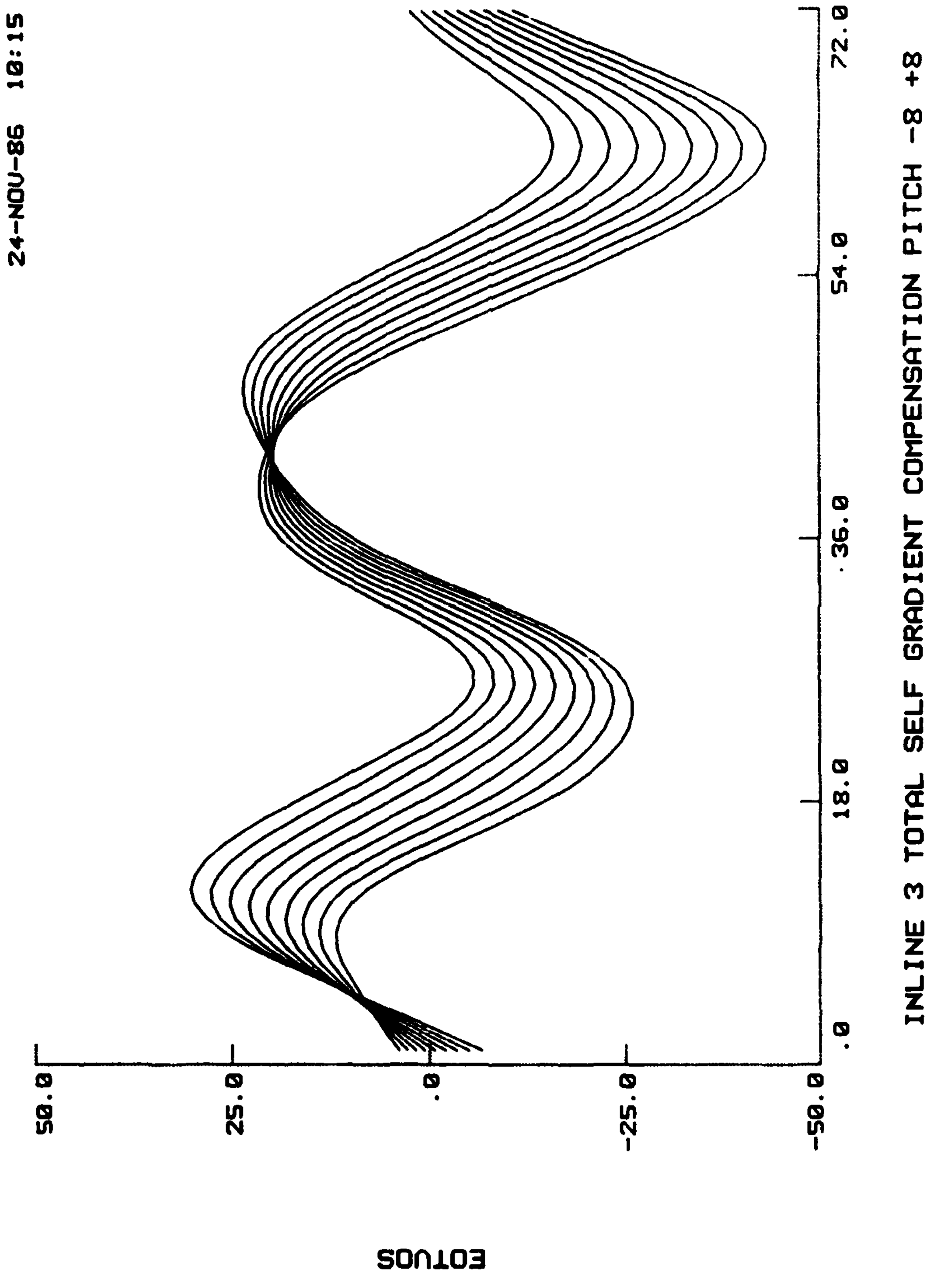


Figure 4-44

Cross 1 Total Self Gradient Compensation Pitch -8 +8

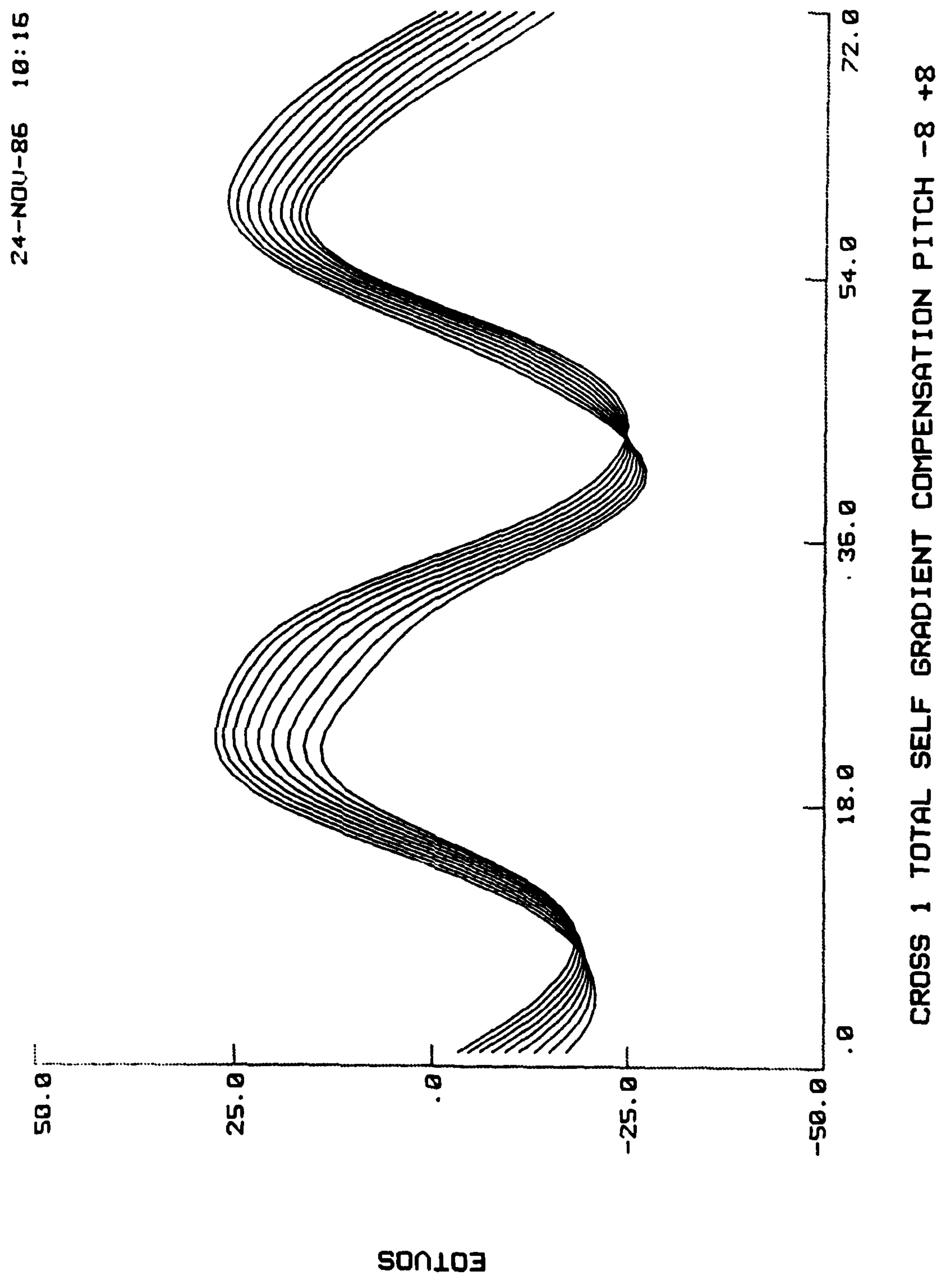


Figure 4-45

Cross 2 Total Self Gradient Compensation Pitch -8 +8

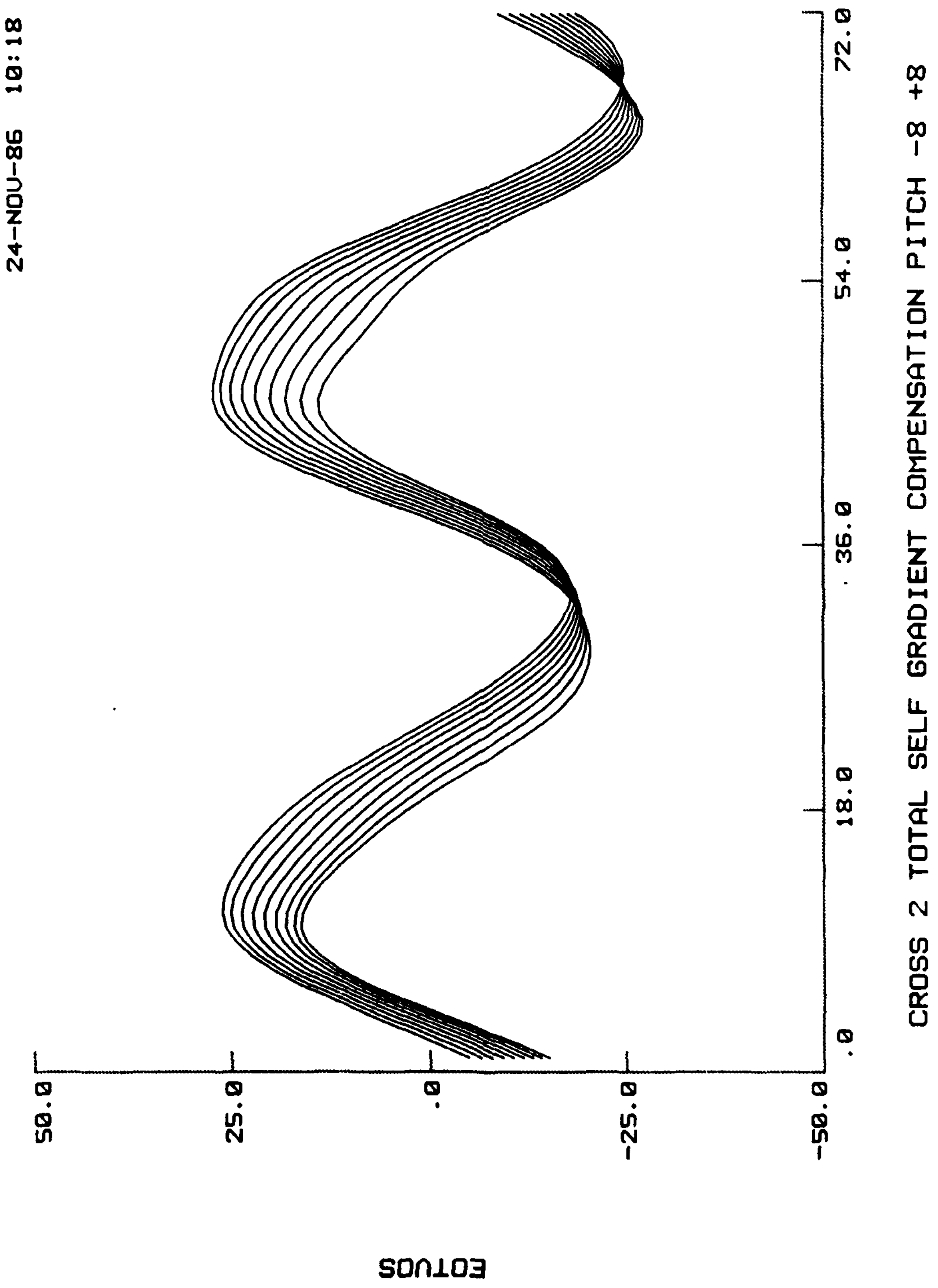
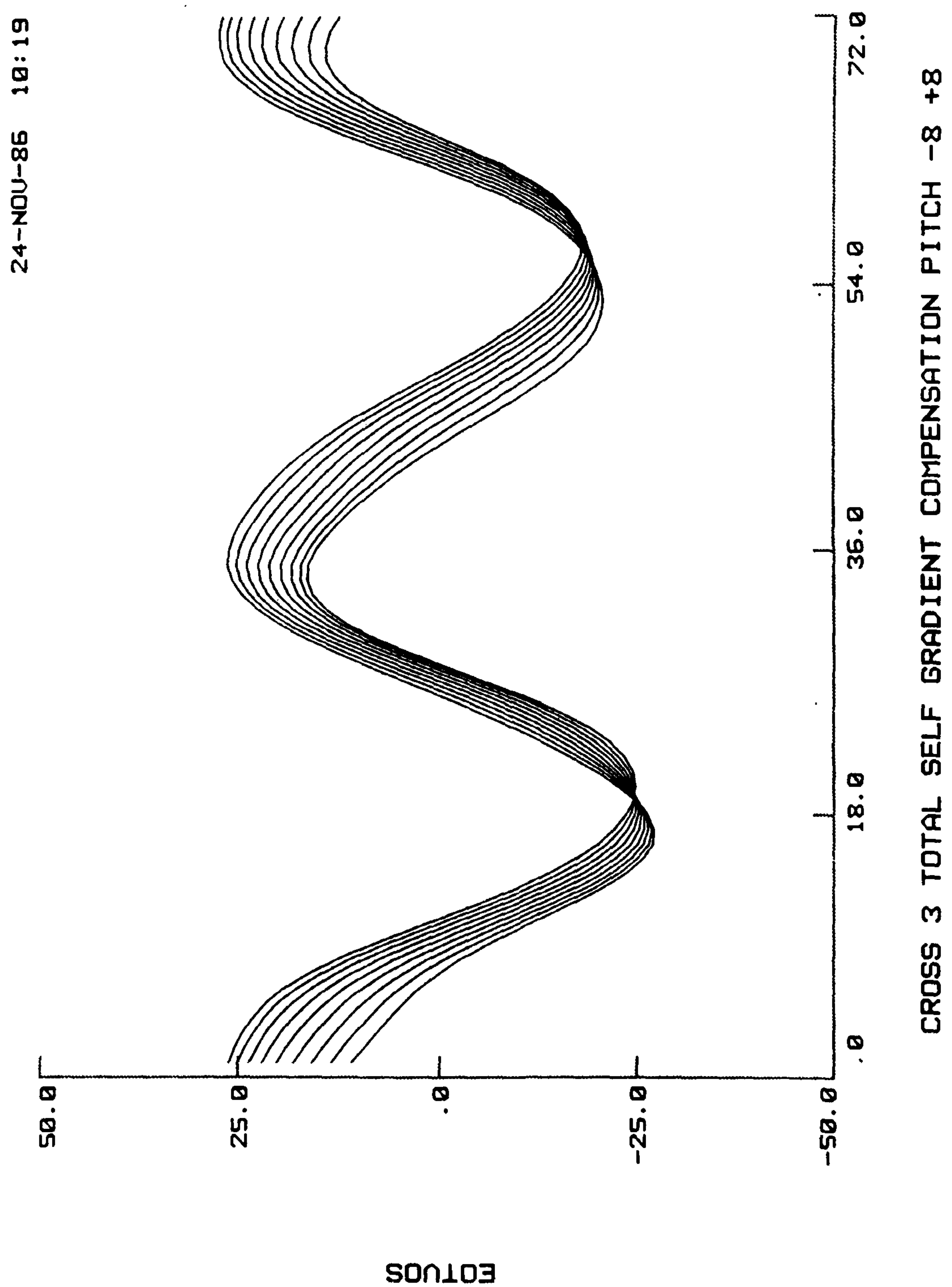


Figure 4-46

Cross 3 Total Self Gradient Compensation Pitch -8 +8



4.7 Field Test

4.7.1 Introduction

This section discusses the tests and findings of the flight test and road tests made prior to the Oklohama surveys and the additional findings in road tests after the van returned to Bell Aerospace. This section does not report these tests in their historical order. For clarity, the presentation discusses problems and solutions with references to their impact on each subsystem at each of these field test phases.

The GGSS system was road and flight tested prior to the Oklahoma surveys and after returning to Wheatfield. The pressure of meeting the Oklahoma survey schedule necessitated resorting to ad hoc solutions to some of the problems uncovered during the first set of tests. These were refined and the refined solutions were road tested in the course of the refurbishment activities.

The problems encountered during these phases were those due to the many electrical and mechanical small detail corrections typcially associated with the first assembly of a complex system and those due to new findings about system performance in the new operational environment.

Major impediments were the absence of the Uninterruptible Power Supply which created transients at the start of each road test; recurring air conditioner problems which contributed to inertial instrument instability; van and platform suspension system problems which aggravated GGI acceleration sensitivities; sporadic, random platform upsets; and the absence of GPS satellites which forced reliance on a bootstrap mechanization (5th wheel) for navigation reference in road tests.

During the airborne tests the absence of satellites, erratic GPS behavior and the narrow time frame in which to pre-flight the system and take-off in time to have some satellite coverage seriously handicapped investigative experiments.

Strong aircraft control from GGSS was very successfully demonstrated. This was further borne out by the subsequent Oklahoma tests.

4.7.2 Problems/Solutions

1. Platform Control Noise problems were experienced throughout the program. The listing of finding and improvements as the program evolved will touch on the noise problem at many points in the following discussion.

   It is critically important to understand that these were tracked down and resolved by completion of the refurbishment phase of the contract. Major performance improvements in potential future application of the GGSS are assured.

   At the planned leveling loop bandwidth (WL) of .015 r/s, noise on the commanded torques to the platform gyros contaminated the laboratory tests. The loop bandwidth was dropped by a factor of four and the tests successfully completed. Three types of noise were observed in the laboratory.

- Glitches. These were major platform disturbances which occured randomly. The smaller glitches corresponded to noise step accelertion inputs of .12 M/S^2. These occured, on average, once per hour and the platform required five minutes to recover. The larger glitches corresponded to noise step acceleration inputs of .48 M/S^2. These occured, on average, about once per six hours and the platform required 20 minutes to recover.

- "High Frequency" Noise. This was periodic noise with mixed periodic varying between 2.5 to 10 minutes. The amplitude varied as a function of leveling loop bandwidth (WL) approximately as

  N= 18Wl + .2, WL> .003R/S.

  where N is degrees/hr peak-to-peak.

- GPS Interference. These were random noise bursts which occurred whenever the GPS asynchronous interrupts were received. At the high values of loop bandwidth, these resulted in platform errors in the order of 800 feet.

2. In the flight tests preparatory to the Oklohama surveys, it was found that the aircraft engines stimulated platform noise which resulted in a peak to peak excursion of 2800 feet in position. Raising loop bandwidth to WL=.02 eliminated the drift completely but restored the problems of 1. An anti-glitch filter was incorporated in the software. This consisted of limiting the maximum acceleration change between successive samples since large sudden changes generally were due to noise spikes. A lead network was added to help dampen the periodic noise.

3. The Oklahoma fights showed a platform misalignment during turns. During refurbishment after the van returned to Bell, the causes were investigated. One possible cause was gyrocompassing an erroneous platform tilt. The erroneous tilt was postulated as due to the disturtion on the accelerometer signals caused by the anti-glitch filter. the anti-glitch filter was elimated and replaced by simple one second smoothing. During this investiagion more of the mehanics of the glitch generation became clearer. The acceleration from each accelerometer is

   obtained by $Ai = \frac{\Delta Ci}{\Delta T}$ where A i is the

   accelertion indicated by the i accelerometer (i=x,y,x), ΔCi is the change in counts from the accelerometer between updates and ΔT is the time between updates.

   It was discovered that paired glitches were caused by ΔT errors. These were due to the time of the previous update being saved after a test flag in the software. When the flag was set an incorrect ΔT was computed. A software change to properly save the time, eliminated paired glitches.

Most single glitches were found to be due to a ΔC error. The velocity counters in the GGIB were changed. Glitches due to ΔC errors were reduced by a factor of 3. These were completely eliminated after GGIB refurbishment following the Oklahoma tests.

The remaining glitches were found to be due to GGIB timing problems. These glitches appeared when the GGIB improperly formatted the data word such that the time of transmission was reported with dropped counts of 64 or 16 counts. The latter corresponding to the smaller, more frequent glitches. To correct this required a GGIB refurbishment. This was done during refurbishment with the results that the glitch noise was eliminated.

4. It was found that "high frequency" noise was aggravated by system hunting due to coarse quantification of D/A gyro signals. A switch was added during refurbishment which rescaled the D/A counters. They had been scaled 1000°/hr of gyro commanding being 10 volts of analog command. The switch changed resistors in the platform electronics so that 100°/hr gave 10 volts. This reduced the quantization of the gyro command by a factor of 10. This reduced the high frequency noise by the same factor.

5. The noise problems were not well handled by the algorithms in the automatic gyro calibration procedures used in the field. In addition, the noise masked a problem with the vertical gyro. With the noise, the gyros appeared heading sensitive and not repeatable. This was not in agreement with the laboratory test results. After the noise problem had been reduced, it was found that the vertical gyro exhibited an anomalous property where the bias changed as much as .1°/hr over 4 hour periods. This resulted in a wandering azimuth when gyrocompassing. The gyro was replaced and a manual procedure used to calibrate the gyros. This proved that the gyros were not heading sensitive and were repeatable. The Oklahoma tests were naturally affected by these gyro, gyro calibration and platform noise problems. However, the GPS and 5th wheel outer loops largely overcame the difficulties. The problems were primarily evident in the Free Inertial mode which was not extensively employed.

6. The basic level and alignment loops algorithms were unchanged throughout the program. During the pre-Oklahoma van surveys the gyrocompassing input to the azimuth alignment algorthm was switched from the total east axis torque to the integrator in the east axis leveling loop. The integrator is a smoothed average of the total torque. The torque set when switching from a navigation mode to free inertial was also changed to obtain a smooth average from the integrators in the respective axis.

7. A software problem was discovered during the refurbishment phase which accounted for the GPS noise. The computation priorities were GGIB, GPS when ready, Platform Control. Since GPS inputs were asynchronous, a GPS interrupt halted platform control operations before these were completed. A flag was written into the code which prevented the GGIB from initiating a new platform control cycle until the last iteration was completed.

8. The GGI acceleration sensitivity, thermal sensitivity and survey results are discussed extensively in Section 5. and 6. Briefly, pre-Oklahoma road tests showed an increase in GGI noise in response to vehicle motions. Corrective action taken were:

   - Experiments with active and passive filters on the bandpass outputs of the three GGIs showed best results with a passive filter with 3Hz rolloff.
   - The $\Sigma\alpha o$ integrators, K4, K8 adjustments were made to minimize GGI noise at van motion frequencies.
   - The axial shake mechanism was locked out.
   - Soft iso-pads were set under each corner of the platform.
   - The softer factory original REVCON van springs were reinstalled.
   - Tests showed no improvement with respect to van motions when isolators were employed under the GGI's themselves.
   - Position sensitivity of GGI's was demonstrated leading to placing the quietest instrument in the noisest location.

9. The ROLM MSE/14 computer is marginal. To handle all the functions required of the land and air surveys, the maximum iteration rate was 4 time per second. Noise problems and choppiness of aircraft control were aggravated by this relatively low rate. The computer also gave priority to operator keyboard entry. This created synchronizing errors with the GGIB after operator entries, contributing to noise problems. The GGIB cleanup during refurbishment solved the priority problem.

4.7.3 Illustrative Results

The airborne tests results required extensive decoding and data processing of the taped data and logically can only be presented in context of data reduction. These are extensively treated in Sections 5.0 and 6.0.

Figure 4-47 shows the van on a road survey. The fifth wheel is shown in good detail in this view.

The first shakedown trip of the van was made in January of 1987. Two crossings of the Lewiston bridge were made and the raw, uncorrected gradients recorded. The Lewiston bridge was selected because of the pronounced gradients signature expected in crossing this chasm. Figure 4-48 is a photograph of the lower Niagara river. The Lewiston bridge is seen crossing the gorge at the far field of the photograph.

Figures 4-49 to 4-60 shown the gradients (inline and cross) of the three GGI's for two traverses. This is raw data. For the first attempt before system corrections and refinements, the repeatability is striking. These may be compared with the refined, data processed results shown in Section 5.0 and 6.0.

Figure 4-47

Van Showing 5th Wheel

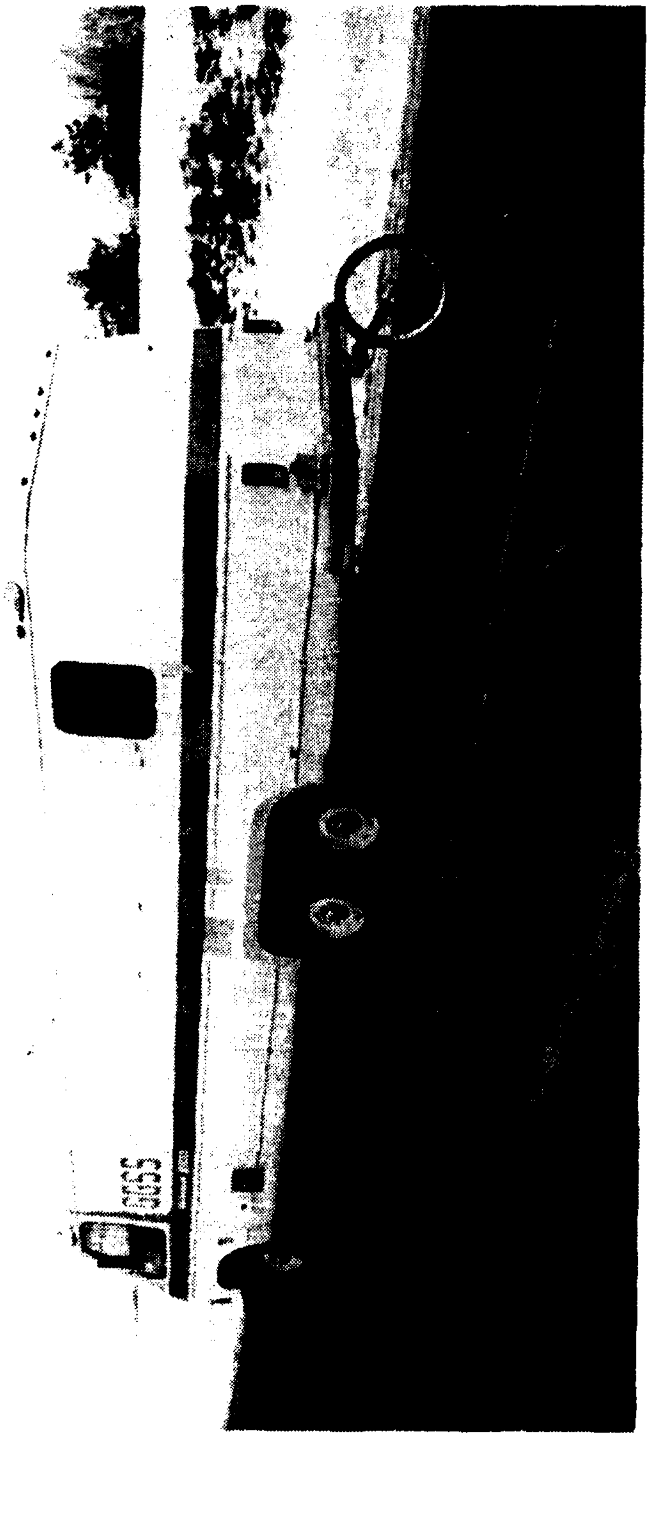


Figure 4-48

Lewiston Bridge and Lower Niagara River

Figure 4-49

Uncorrected Gravity Gradient Measured on GGSS Shakedown Drive

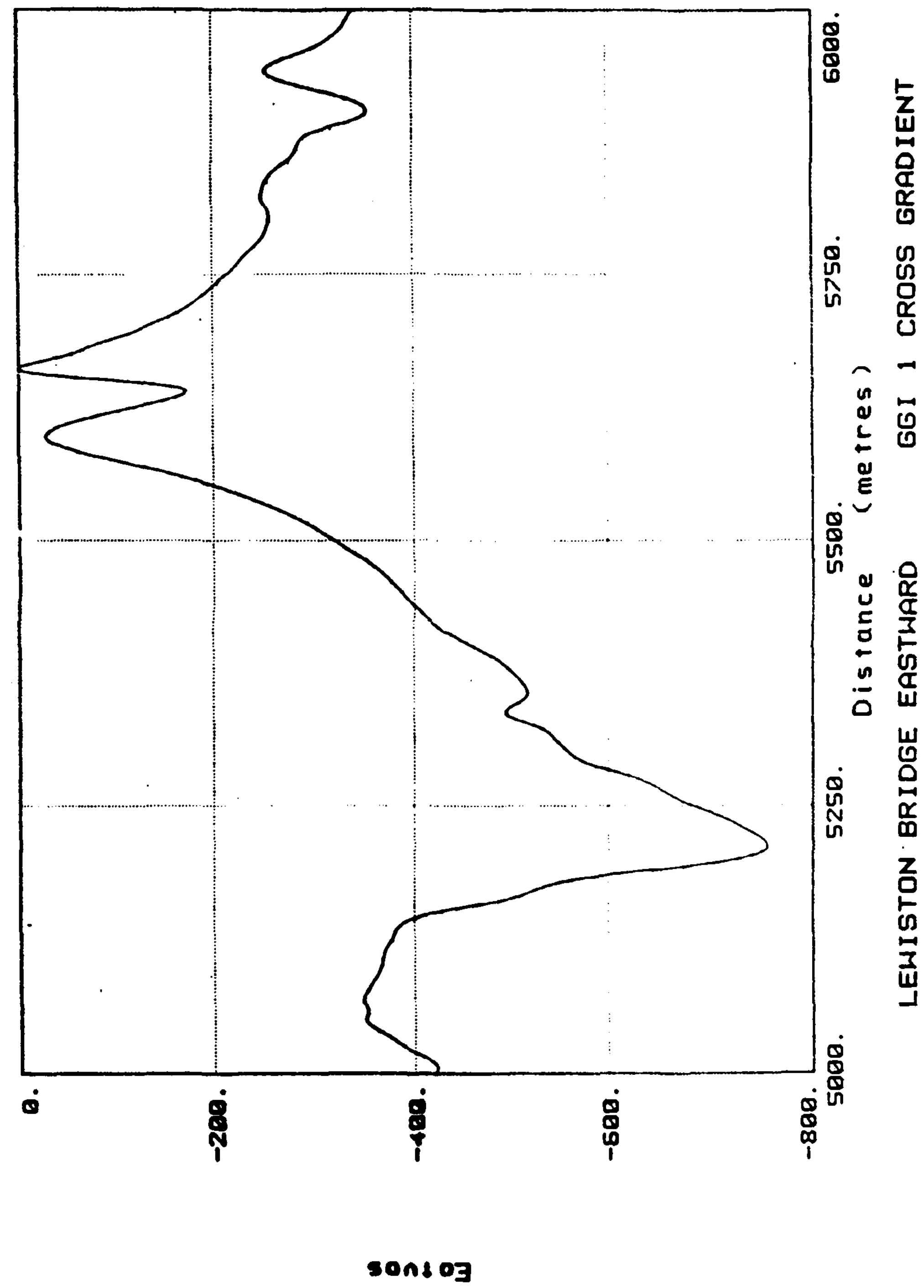


Figure 4-50

Uncorrected Gravity Gradient Measured on GSS Shakedown Drive

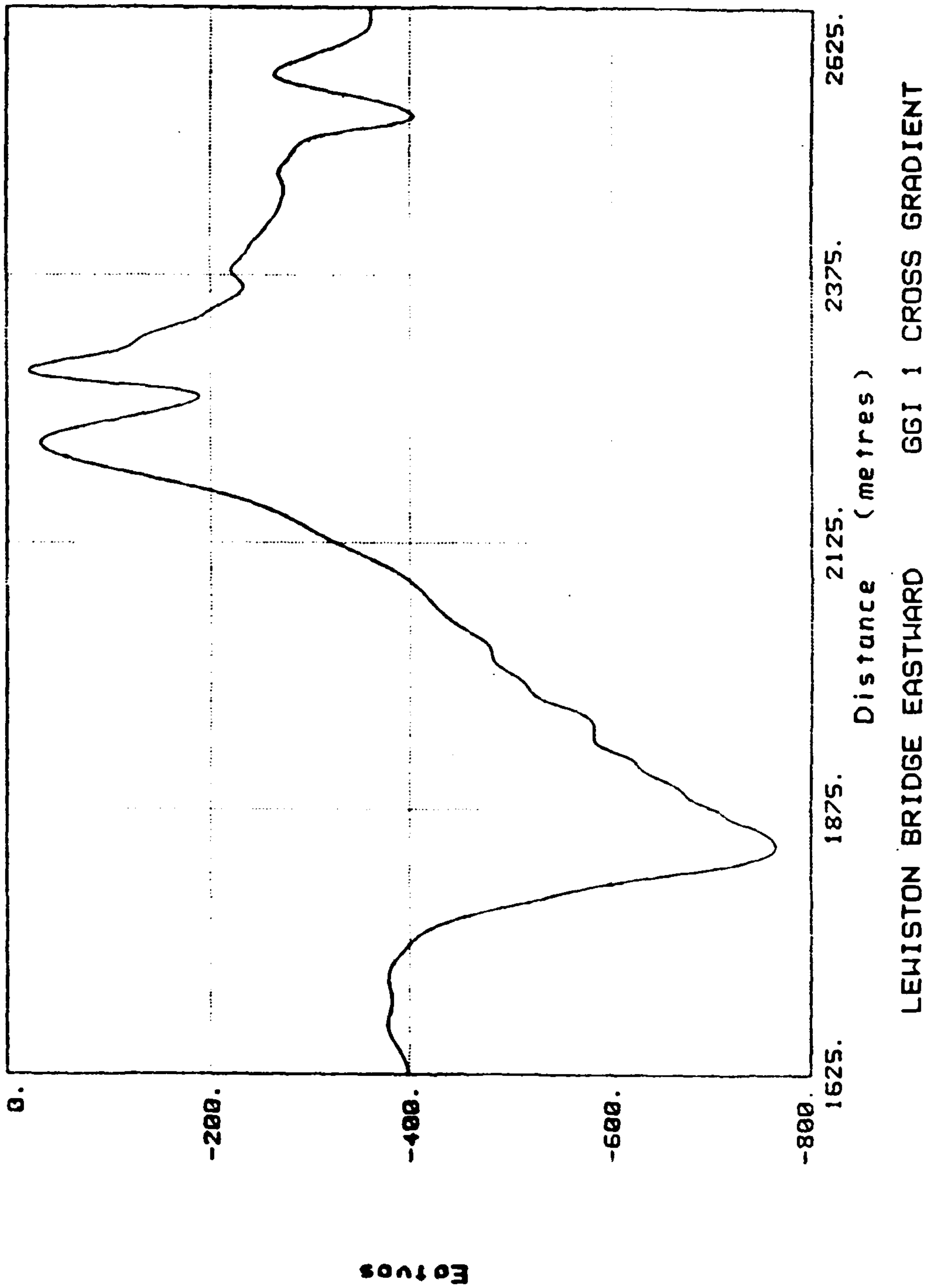


Figure 4-51

Uncorrected Gravity Gradient Measured on GGSS Shakedown Drive

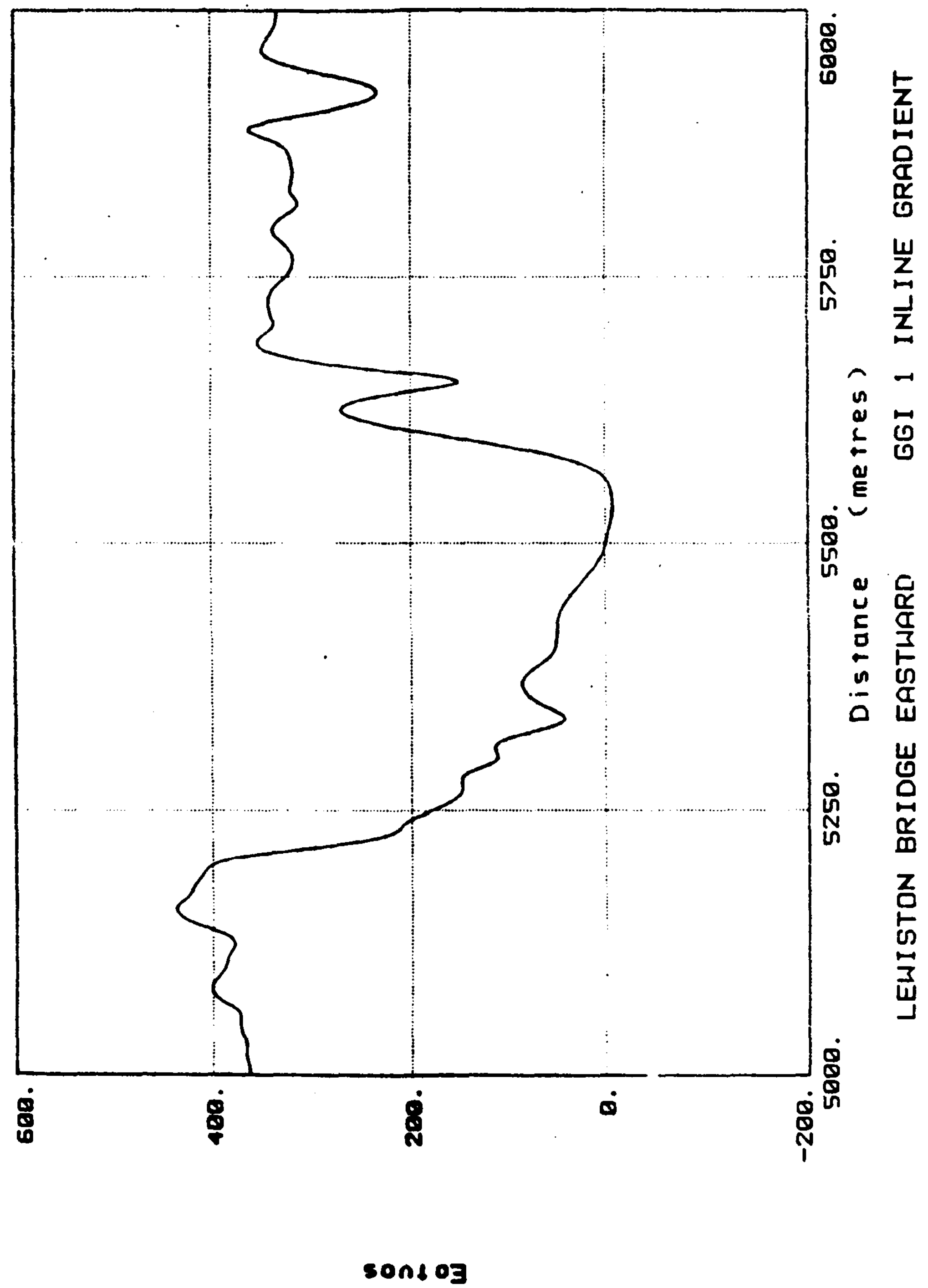


Figure 4-52

Uncorrected Gravity Gradient Measured on GGSS Shakedown Drive

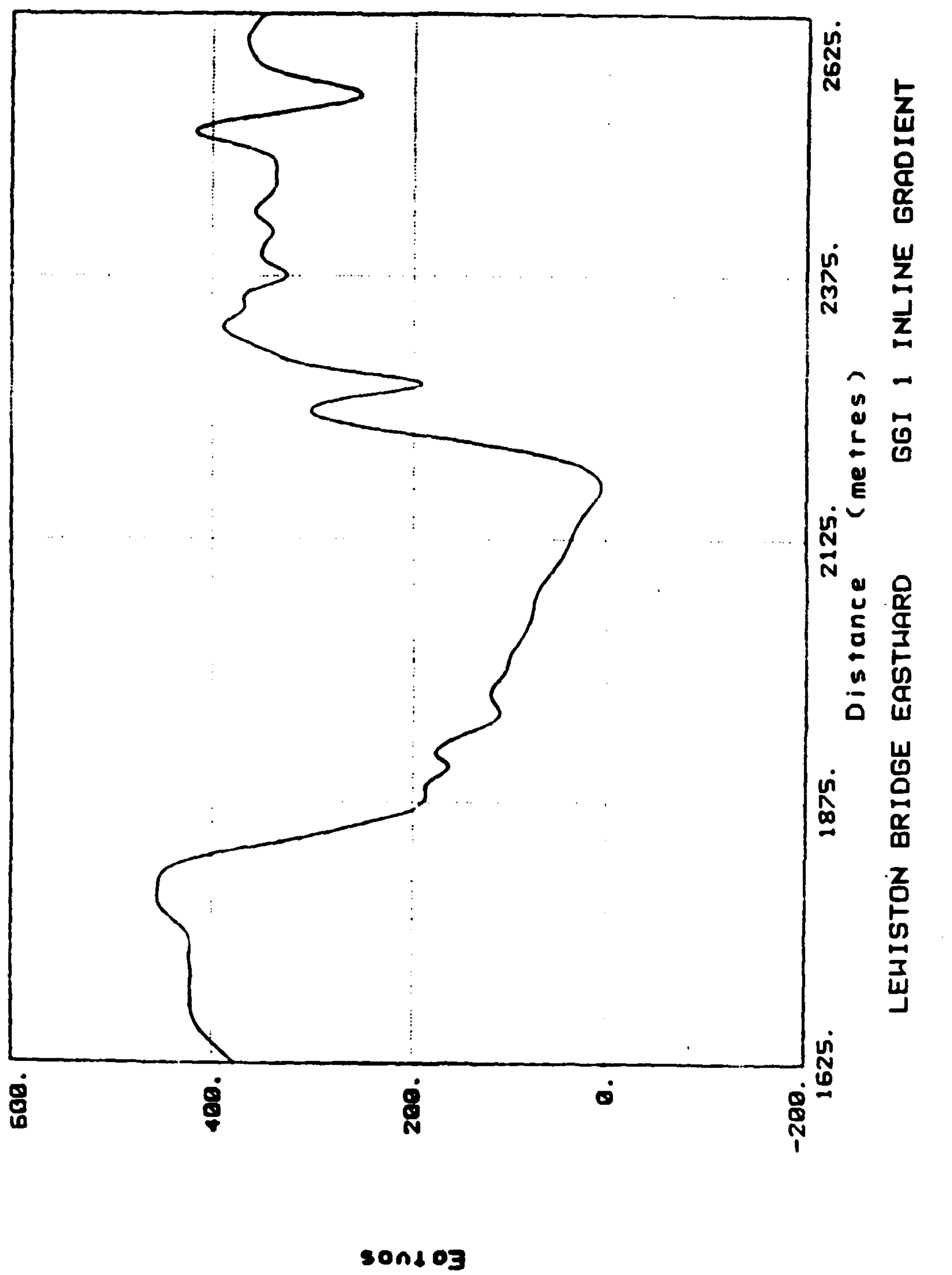


Figure 4-53

Uncorrected Gravity Gradient Measured on GGSS Shakedown Drive

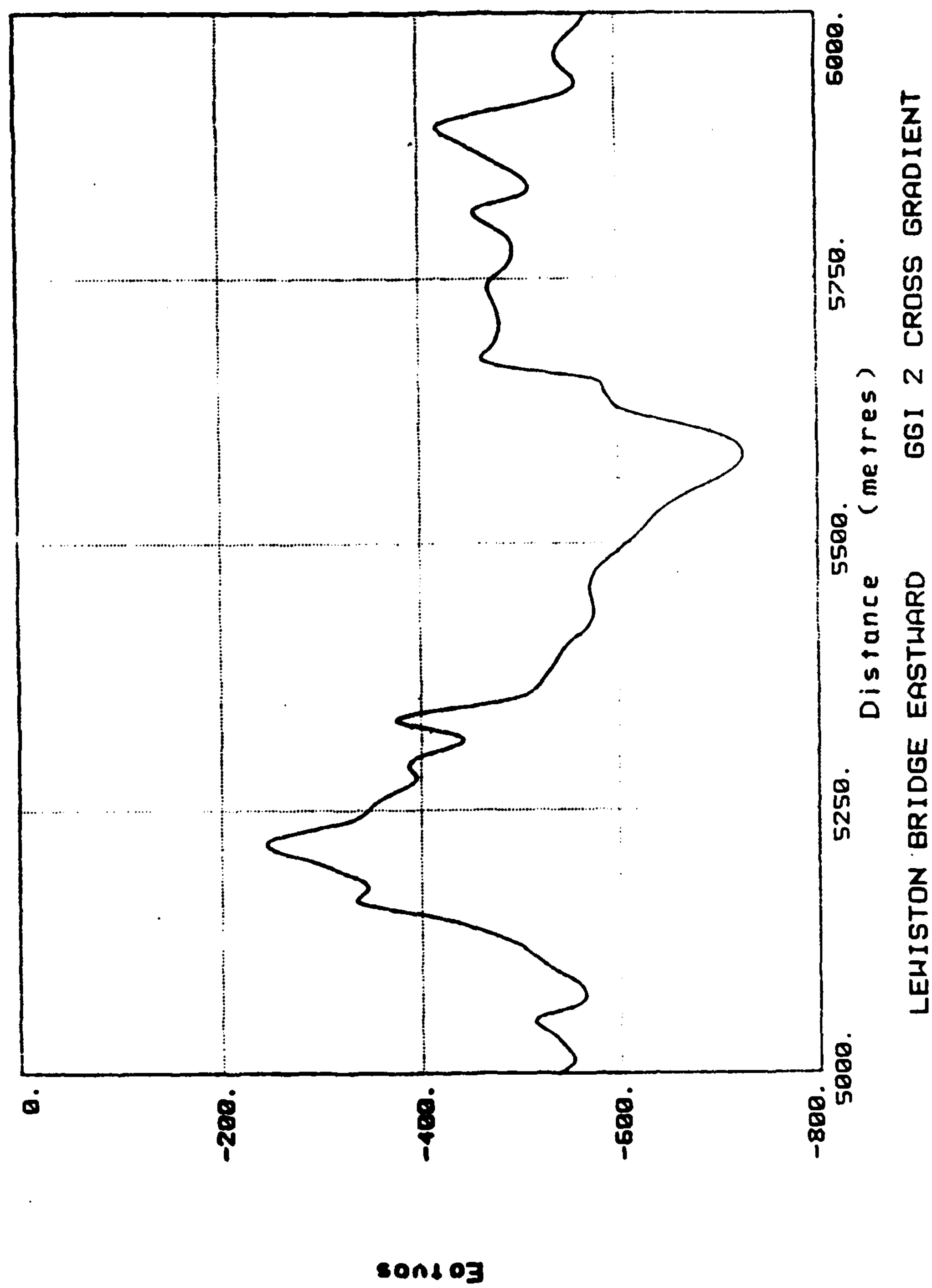


Figure 4-54

Uncorrected Gravity Gradient Measured on GGSS Shakedown Drive

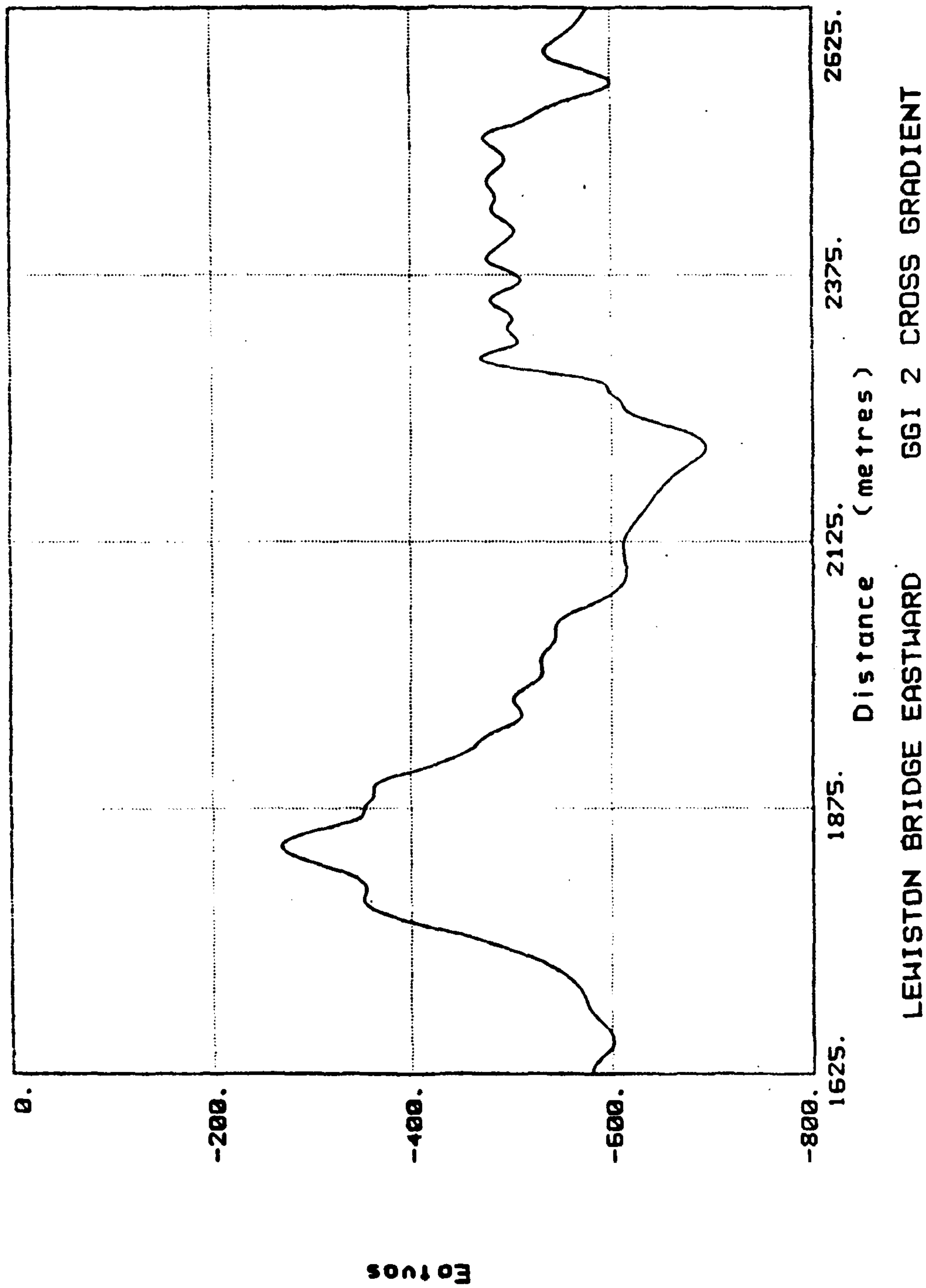


Figure 4-55

Uncorrected Gravity Gradient Measured on GGSS Shakedown Drive

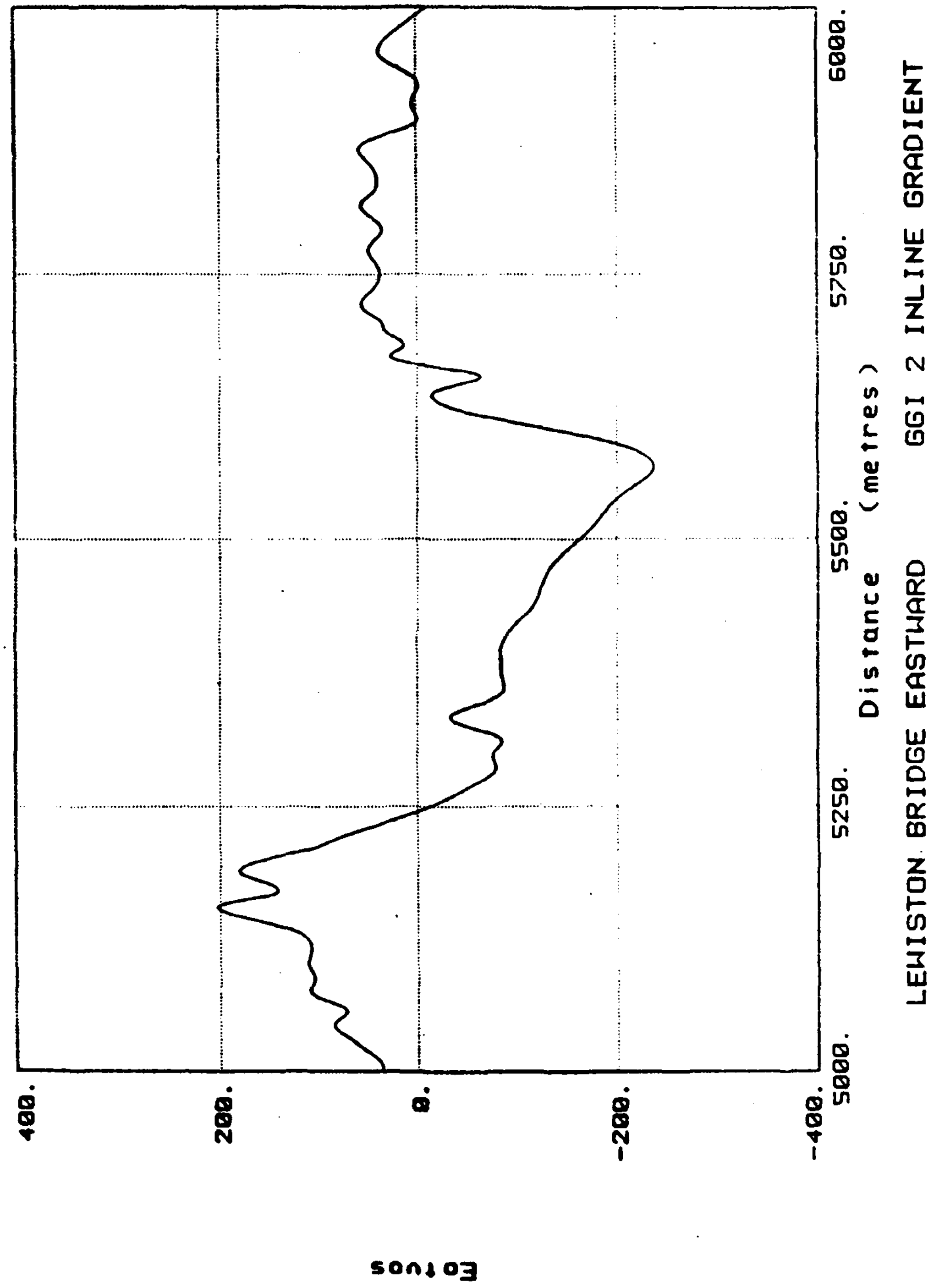


Figure 4-56

Uncorrected Gravity Gradient Measured on GGSS Shakedown Drive

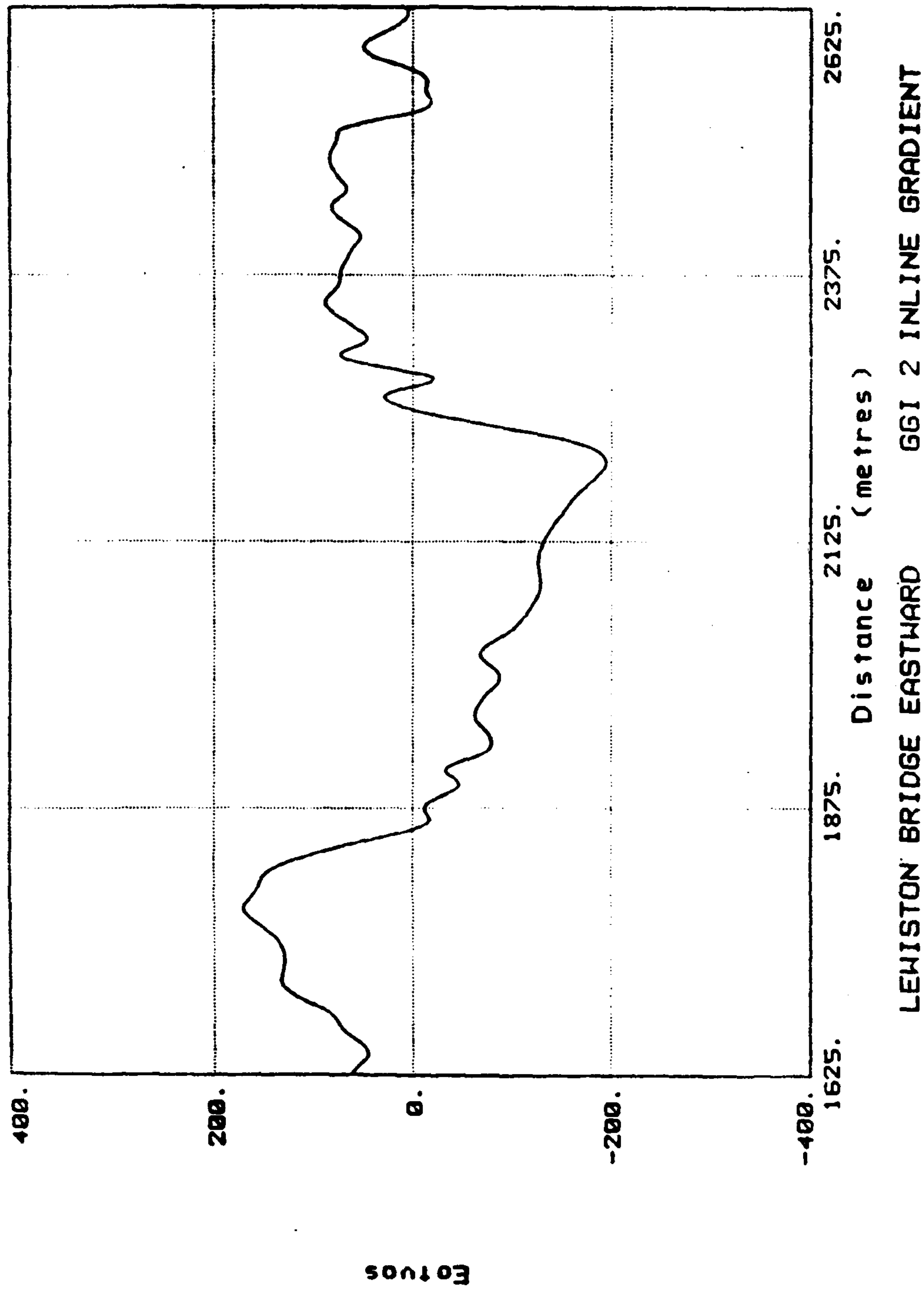


Figure 4-57

Uncorrected Gravity Gradient Measured on GGSS Shakedown Drive

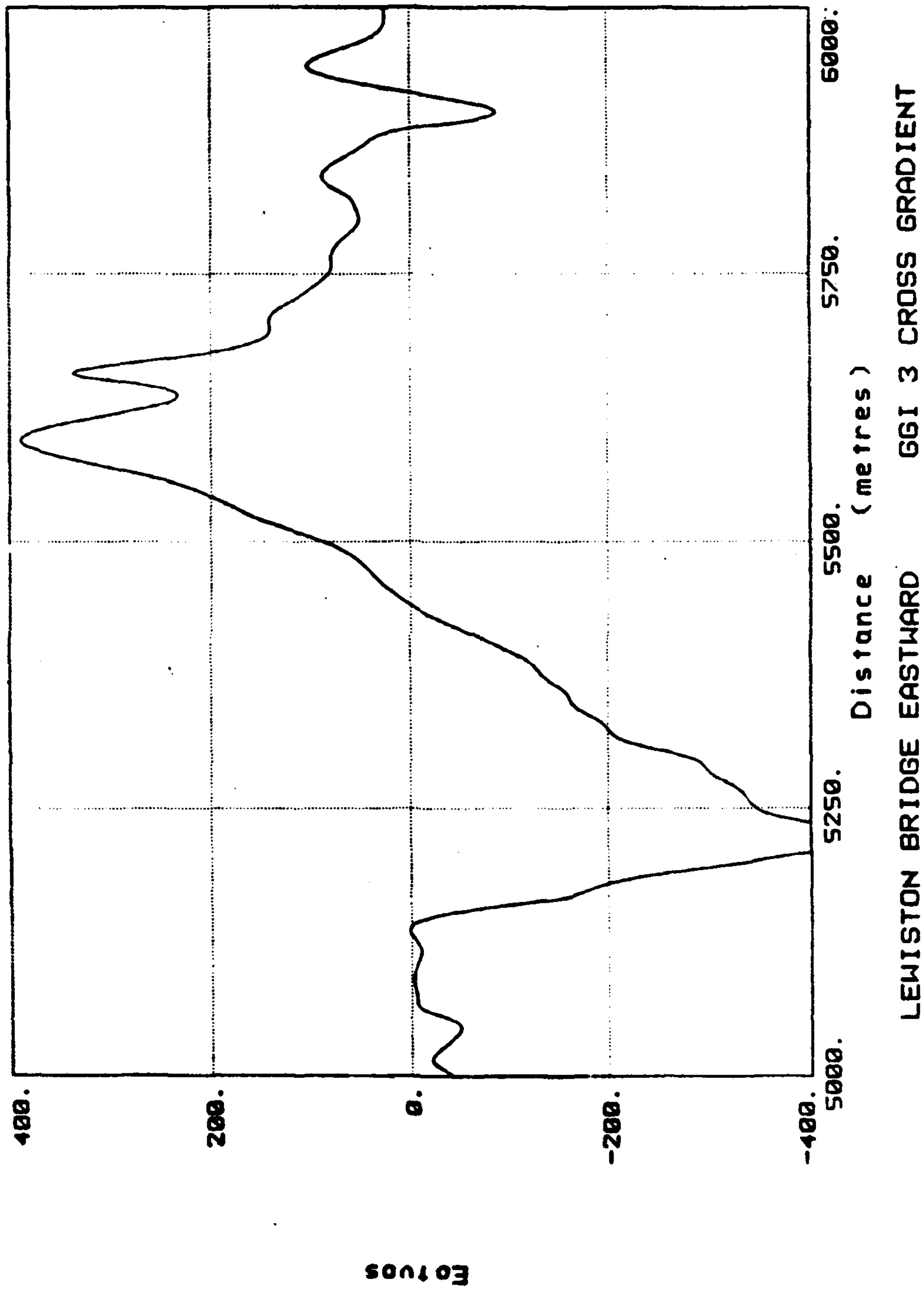


Figure 4-58

Uncorrected Gravity Gradient Measured on GGSS Shakedown Drive

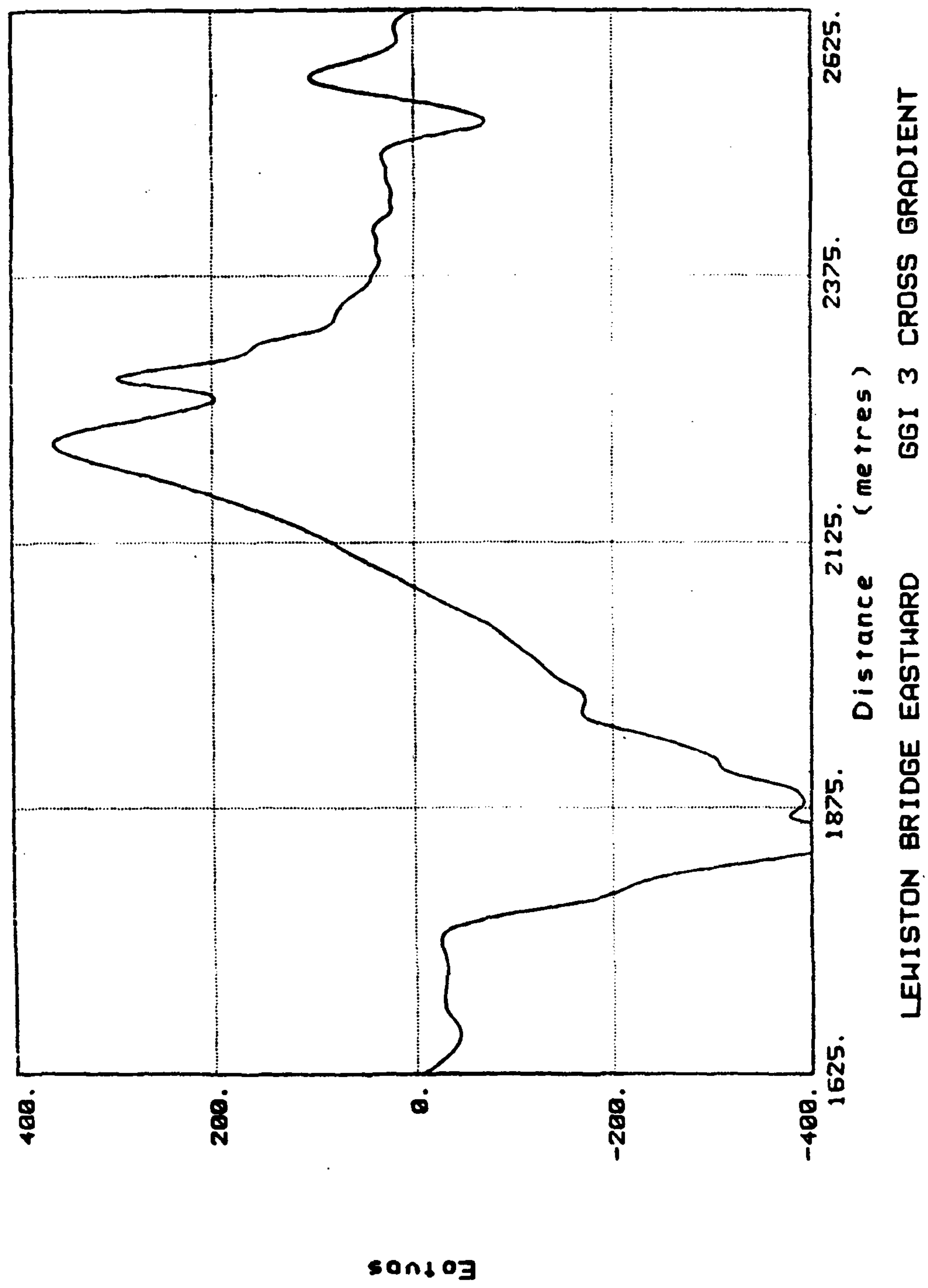


Figure 4-59

Uncorrected Gravity Gradient Measured on GGSS Shakedown Drive

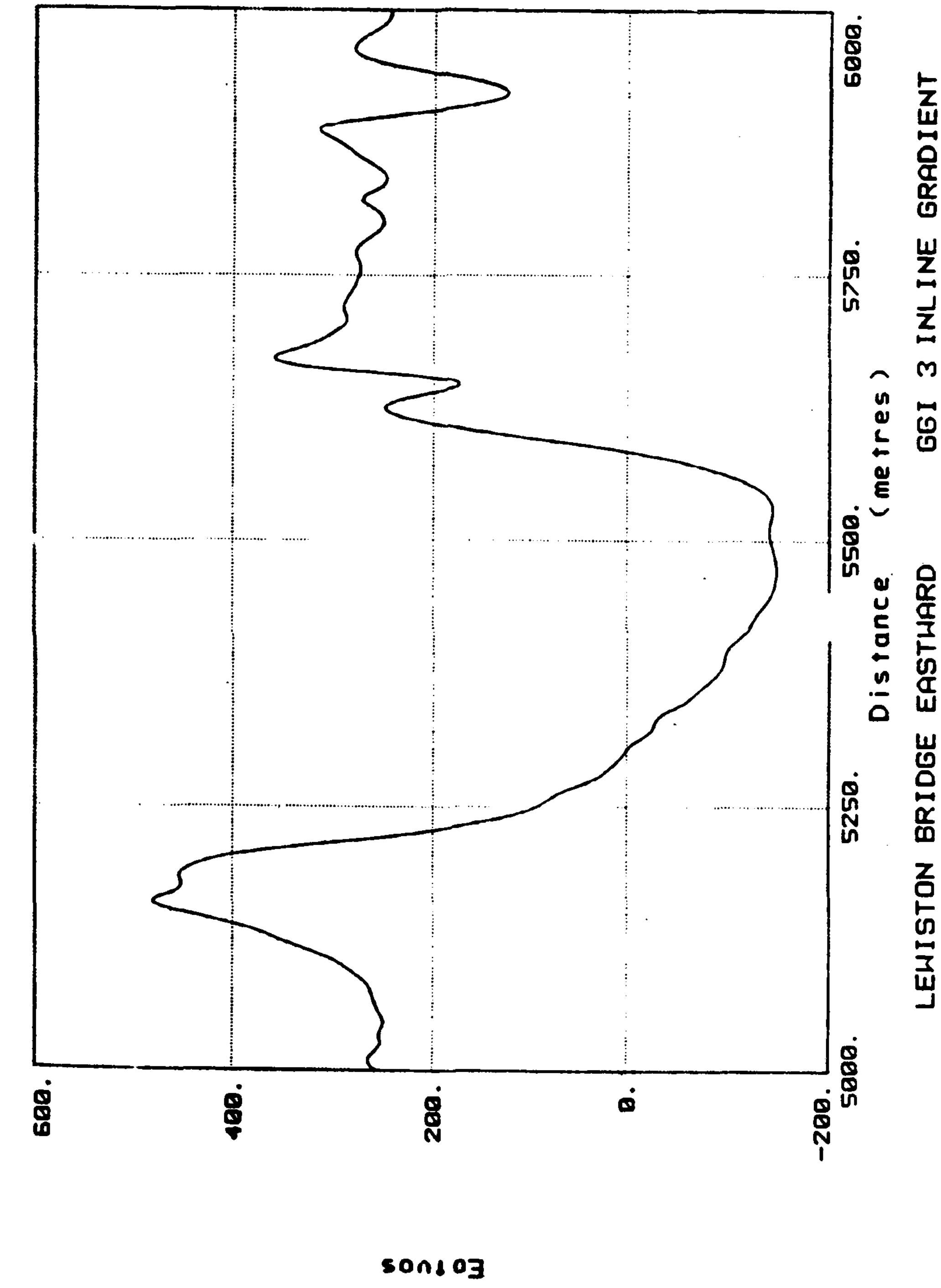
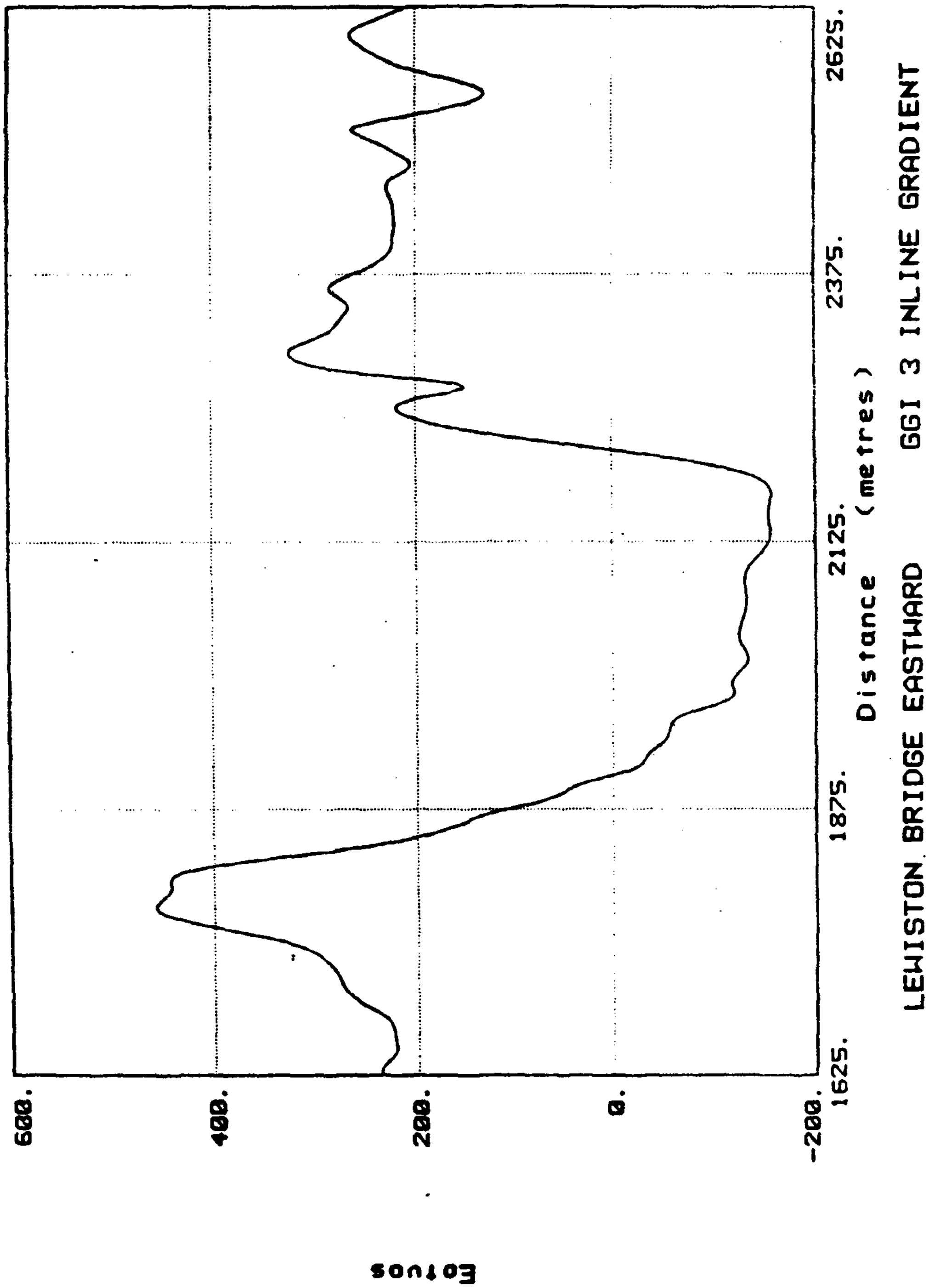


Figure 4-60

Uncorrected Gravity Gradient Measured on GGSS Shakedown Drive



Figures 4-61 and 4-62 show the effectiveness of navigation using the fifth wheel as reference. Shown are the latitude and longitude plots of traverses made on 12-15-87 from the Bell plant at Wheatfield, NY to Hartland, NY and back. The numbers on these figures shows the known fixed points, established by GPS, which were used for updates. The location of these waypoints are listed in Table 4-9. The round trip distance was approximately 50 NM. It is important to note that all the improvements cited were not yet in place at the time of this test. The most far reaching change made was the refurbishment of the GGIB. Results using the improved GGIB could not be obtained in time for this report. Hence the plots of Figures 4-61 and 4-62 show evidence of glitches particilarly in azimuth drift. It is also important to note that optimum update procedures were not used. However, the procedures used were very practical for rapid surveys which are the program objectives.

Specifically the van did not dwell at update points until possible transients were settled. Instead when the van reached the update point, the corrected coordinate were instantaneously entered and the van departed immediately.

Nonetheless, the results were good. The outbound and inbound directions agree to within 300 feet or less for most of the traverse except for the azimuth drift between waypoints 12 and 13 on the return trip. The sharp change at point 13 reflects the update at this point. This is the worst point and required a correction in position of about 1100 feet.

A measure of the precision of navigation may be obtained by examining the discontinuities at the other waypoints. The discontinuities are due to updates at these points. On the scale of the figures, the correction steps are barely discernible except for the already discussed point 13.

Table 4-9

Hartland Run Waypoints

Waypoint	Known Fixed Point Number	LAT 43.XX° XX	LON-78.XX° XX
Bell Aero/Wal. Niagara	1,2,17	.101	.927
Walmore-Lockport	3,16	.121	.927
Lockport-Ward	4	.121	.891
Town Line-Niagara Com. Col.	5,15	.144	.885
RT104-Peking	6,14	.202	.885
RT104-RT93	7,13	.211	.796
RT104-2212 Marker	8,12	.219	.690
RT104-55MPH Sign	9,11	.250	.638
Hartland Dept Pub Works	10	.242	.533

Figure 4-61

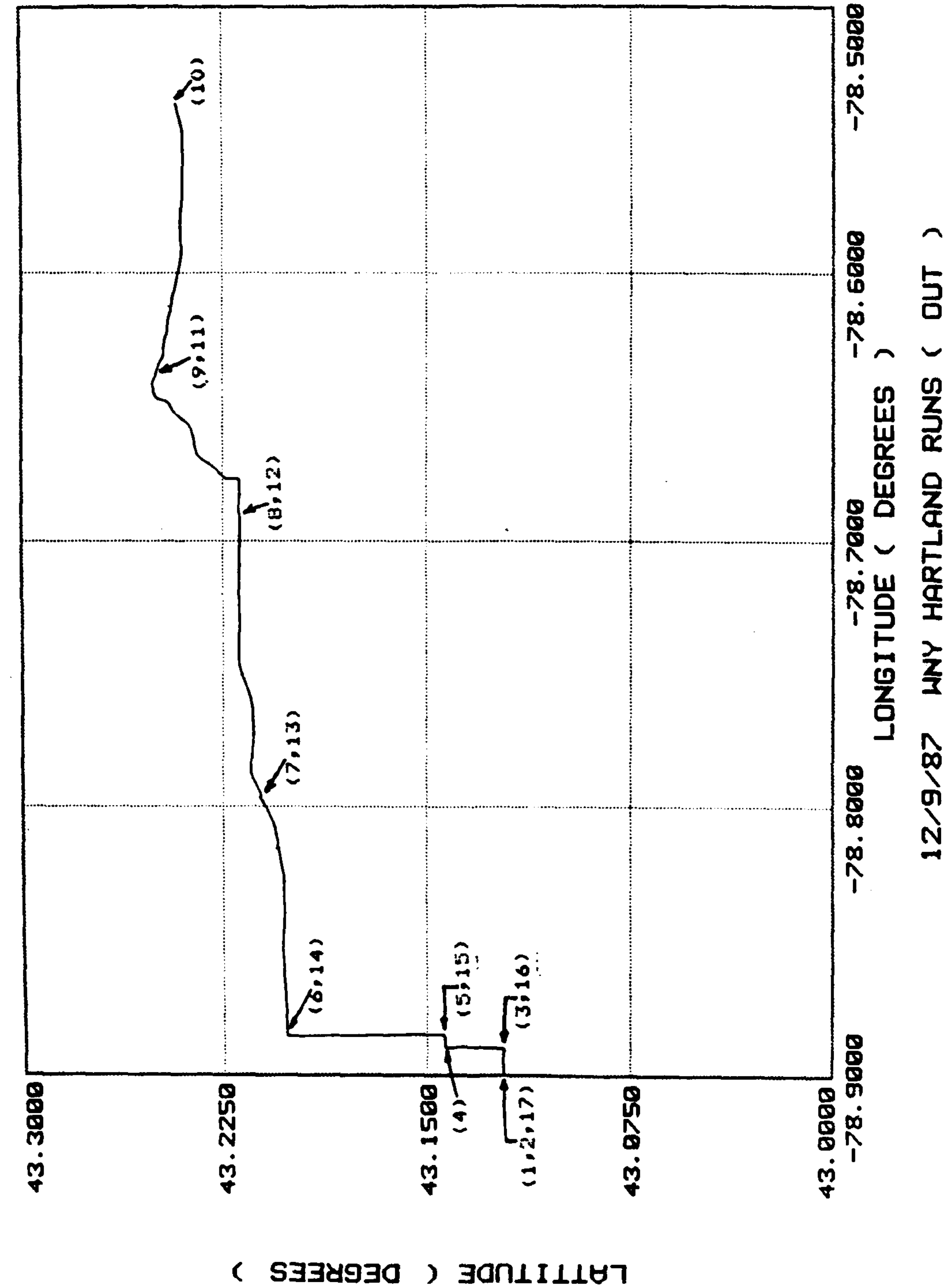
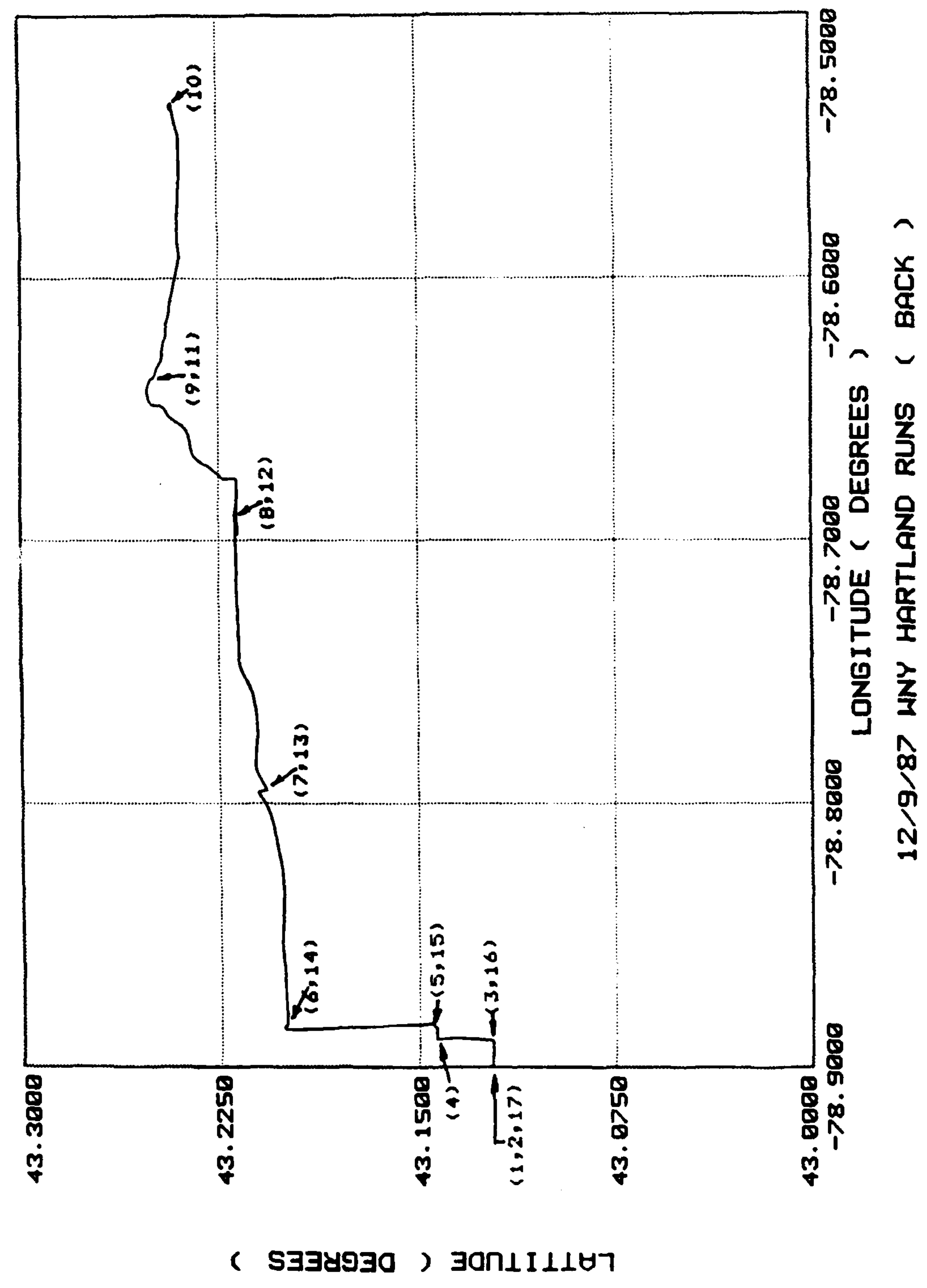

43.3000
43.2250
43.1500
43.0750
43.0000
-78.9000
-78.8000
-78.7000
-78.6000
-78.5000
LONGITUDE (DEGREES)
12/9/87 WNY HARTLAND RUNS (OUT)
LATTITUDE (DEGREES)
(10)
(9,11)
(8,12)
(7,13)
(6,14)
(5,15)
(4)
(3,16)
(1,2,17)

Figure 4-62


43.3000
43.2250
43.1500
43.0750
43.0000
-78.9000
-78.8000
-78.7000
-78.6000
-78.5000
LATTITUDE (DEGREES)
LONGITUDE (DEGREES)
12/9/87 WNY HARTLAND RUNS (BACK)
(1,2,17)
(3,16)
(4)
(5,15)
(6,14)
(7,13)
(8,12)
(9,11)
(10)

5.0 AIRBORNE GRAVITY SURVEY

Planned airborne testing was to be carried out in two phases with Phase I in Western New York and Phase II in Oklahoma.

5.1 Test Plan

Flights conducted in Western New York were primarily shakedown flights discussed in section 4 of this report. The planned Phase I repeat track airborne testing (discussed in the "System Test Plan" Bell Report #6496-928004) was deferred to the Phase II testing local. Weather conditions at the end of Phase II resulted in cancellation of the airborne repeat track testing.

Phase II test consisted of a survey of a 315Km square in the Texas Oklahoma Panhandle. The test plan for Stage 2 airborne is discussed in section 8 of the Test Plan Report.

5.1.1 Local, Flight Patterns, Procedure

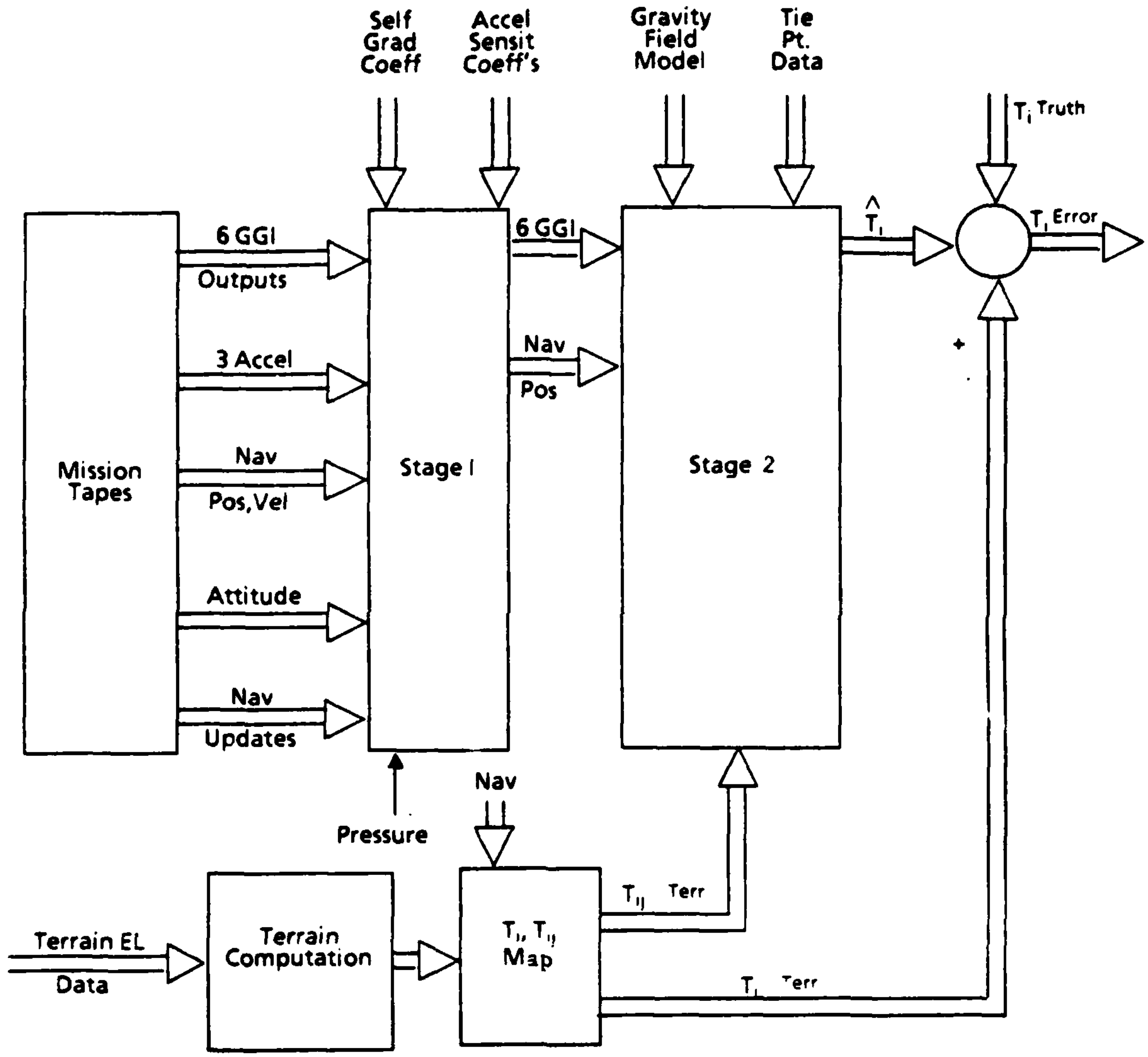
A 315Km square pattern was surveyed out of the Clinton-Sherman airport in Oklahoma. The survey was centered at latitude 34deg 48min 54sec N longitude 98 deg 48min 6sec W. Track end points required by the on-line computer system for flight control and in post mission processing were based on a DMA-supplied mapping which related survey grid coordinates and geographic coordinates. A tabulation of the track end points is given in Table I. Altitude of the survey was 700m above mean terrain.

5.1.2 Data Reduction Requirements

Figure 5-1 shows a high level block diagram of the post mission airborne software. Stage 1 recorded input consists of GGI, accelerometer, navigation, and attitude signals sampled at 16/sec rate. Output from Stage 1 consists of 6 GGI outputs demodulated, filtered, compensated for self gradient and centripetal gradient and acceleration sensitivity. Outputs of Stage I are synchronized values of GGI output and navigation values sampled at once/second rate.

Stage II integrates gradients along track, uses track crossing data to constrain low frequency error, incorporates tie point data and terrain corrections. Details of the airborne post mission processing are given in Bell Report No. 6496-928008, "Functional Description, Stage 1" and 6496-928009 "Functional Description, Stage 2 (Air)" Data Reduction Computer Programs.

Figure 5 -1



8227-5-1

5.2 Conduct of Airborne Survey

5.2.1 Survey Site Preparation

Several trips were made by Bell and AFGL to the Clinton Sherman Airport in Oklahoma well in advance of the GGSS equipment arrival. These trips established contact points and working relationships with the following local agencies:

- o MODA (Midwest Oklahoma Development Agency) who manage the airfield and adjacent facilities including on-site housing and office space.
- o Kleek Aviation, Inc. (aircraft & refueling services).
- o Telephone & Electric utility companies.

The advance trips were also necessary to define GGSS van and aircraft parking site, ground power and telephone hook-ups, candidate roads for land survey tests, and locations for Astro-Geodetic Survey points. The "Astros" were subsequently surveyed-in by DMA's Geodetic Survey Squadron based in Cheyenne, Wyoming.

The best parking site for the GGSS was found to be the "Compass Rose", an ideal spot located away from the control tower, hangars, and day-to-day ground traffic of taxiing aircraft and support vehicles. See Figure 5-2. The local telephone and power companies were contracted to run service to (and install meter and junction boxes at) the edge of the compass rose concrete apron which was within 25 feet of the parking spot.

Electrical power was 2 phase 60 cycle 120/208 volt service which connected directly to the GGSS van through Bell-supplied cable. This enabled continuous operation of van lighting, air conditioning, and GGSS equipments while parked and awaiting conduct of the next survey segment. The C-130 aircraft used no utility power; a diesel-powered 400 cycle ground cart was used only just before take-off to initiate preflight power-up sequence.

5.2.2 Survey Flight Record

The Southern Air Transport C-130 took off from Niagara Falls International Airport with the GGSS van and equipment on board and, after a 5 hour flight, touched down at Clinton-Sherman Airport early in the morning of Saturday, April 4th, 1987. On Sunday, April 5th the first airborne survey flight was conducted with four 300 KM-long tracks completed.

A total of 31 flights were conducted between April 5th and May 20th of 1987 with 121 tracks completed (out of 128 planned). On May 21st begin a stretch of intense rain and low visibility that kept the system grounded. On May 28th, with no forecasted improvements in weather, the decision was made by DMA and AFGL to terminate airborne operations and proceed with the land survey. The van was removed from the C-130 and the aircraft returned to SAT headquarters in Miami, Florida.

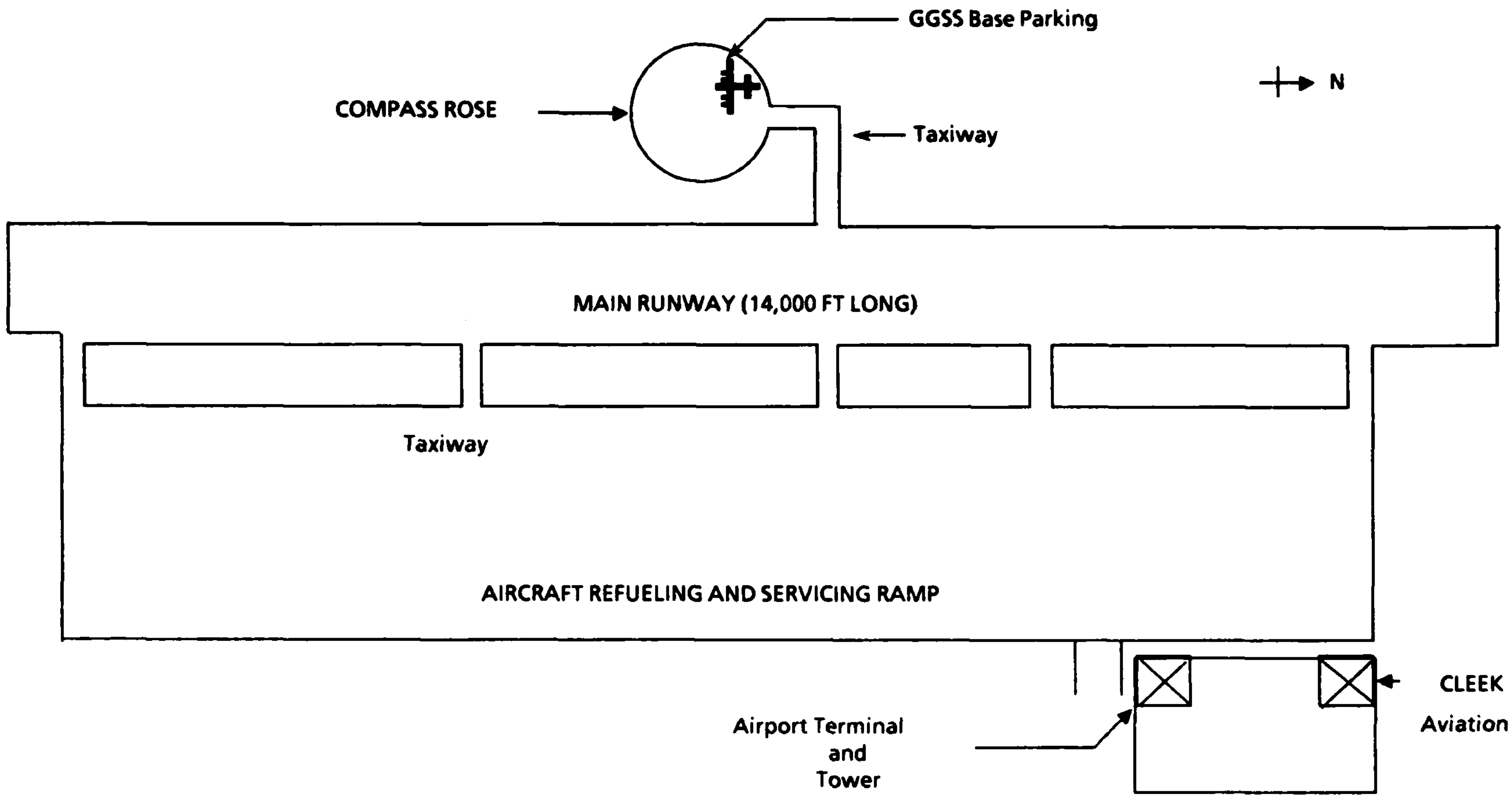


Figure 5-2 Clinton - Sherman Airport Layout

8227-5-2

For the 46 days that constituted the airborne survey interval (April 5th to May 20th) the following record was compiled:

• Conducted survey flights	31 Days
• Grounded by bad weather	6 Days
• Aircraft equipment problems	5 Days
• GGSS equipment problems	4 Days
• Total	46 Days

Flights were limited to one per day as dictated by GPS satellite availability. For the time of year and locale, good GPS Position Dilution of Precision (4 satellites) occurred, on average, from 10 pm until 2 am. A typical day for the field crew:

1:00 PM	Breakfast
2:00 PM	Check subsystem functions and groom GGSS for next scheduled flight.
5:00 PM	Break for casual time and dinner
9:00 PM	Commence pre-flight, acquire GPS satellites as they rise on horizon.
9:45 PM	Start aircraft ground cart. Perform GGSS power switch-over to aircraft.
10:00 PM	Take-off.
10:00 PM to 2:00 AM	Survey as many tracks as GPS availability allows (typically 4 to 6 legs).
2:00 AM	Return & land.
2:30 AM	Complete switch over to ground power. Set-up overnight system diagnostic test, if required.
3:00 AM	Retire.

5.2.3 Field Problems and Solutions

The number one problem experienced in Oklahoma throughout the airborne survey was erratic GPS performance. Of 31 total flights, only 12 were judged by the field crew as uncompromised by suspicious GPS behavior or total outages. Two or three phone calls per week to the GPS control center at Colorado Springs were required to find out which SV's (satellites) were healthy, unhealthy, being reprogrammed, etc.

From pre-survey experiences with GPS back in Western New York, it was determined that the GPS altitude solution was not always reliable even when latitude and longitude seemed correct and stable. We decided to fly baro-altimeter, which was the mode used for all survey flights.

Although we could not separate error sources, probably as many GPS problems were due to the TI-4100 receiver as due to satellites. An upgraded prom board has since been purchased from Texas Instruments and installed in the receiver for improved satellite acquisition and dynamic tracking (yet to be tested).

Other problems encountered in Oklahoma were:

FIELD PROBLEM	CORRECTIVE ACTION	REPAIR TIME
Van Interior Over Temperature Due To Inoperative Aircraft Air Conditioner	Cardboard Lash-up Ductwork to vent Power-Rack (UPS) Exhaust heat Overboard	1 Day
GGI No 2 Noisy Slip Ring	Replaced with spare Slip Ring	0
U.P.S. Failure (2 separate events)	1. Sent Failed Chassis to Vendor for repair (Air-Ex.)	3 Days
	2. Fixed Second Failure in place.	
Aircraft Engine Failure	Replaced Engine	3 Days
Aircraft Instrument Failure	Replaced Faulty Panel Indicator	1 Day
Broken Propeller Nose Cone (Bird Impact)	Replaced Cone	1 Day

5.3 Data Reduction

Survey tracks were numbered from the south west corner of the 315 km square. The 64 tracks in the north-south direction were designated NS, those running east-west were designated EW. Table 1 is a tabulation of the geographic coordinates of the end points for the survey tracks based on a DMA supplied mapping between geographic and survey pattern coordinates.

Table 2 lists those tracks and partial tracks where the data was judged good enough to use in Stage II processing.

5.3.1 A description of the Stage I processing is given in Bell Report 6501-928007. Output consists of 1 sec synchronized samples of filtered gradient measurements, position, velocity, attitude, etc. Plots of the gradiometer outputs are shown in Figures 3 through 48. Three GGI outputs are shown in each plot with each output bias offset by 400 E to facilitate presentation on a single graph.

5.3.2 Stage II Processing

A description of Stage II processing is given in Report 6501-928008. Incomplete input to Stage II processing precluded a complete and comprehensive analysis. Using the available data in Table 2, model constrained along track integration was carried out. Track crossing constraints at the disturbance vector level were used to control the low frequency error along each track. Finally the data was corrected to minimize an overall polynominal surface fit. The resulting solution for each track is shown in Figures 49 through 81. Three tracks of data are plotted on each graph with a 100 mgal offset. The disturbance vector solutions presented here have not been compared against truth data.

The Analytic Sciences Corporation (TASC) used Stage I output to solve for the disturbance vector in a portion of the test area using their "Template Approach". These results were compared against 5' x 5' mean gravity disturbance components at the earth's surface. Results of this analysis were presented at the "Sixteenth Moving Base Gravity Gradiometer Review" and are reported in TASC Report SP-5362-7 "Gravity Gradiometer Survey System (GGSS) Airborne Test Data Reduction Results".

TABLE I

WAY POINTS FOR GGSS OKLAHOMA SURVEY AREA-315KM SIDES

SOUTH to NORTH TRACKS (written from south-west corner)

TRACK	SOUTH: LATITUDE LONGITUDE	NORTH: LATITUDE LONGITUDE
SN- 1	33.3681355	36.2071740
	100.4758060	100.5348465
SN- 2	33.3688839	36.2079478
	100.4220367	100.4792535
SN- 3	33.3696073	36.2086966
	100.3683679	100.4236600
SN- 4	33.3703076	36.2094205
	100.3146462	100.3680652
SN- 5	33.3709833	36.2101195
	100.2609236	100.3124695
SN- 6	33.3716349	36.2107935
	100.2072002	100.2568727
SN- 7	33.3722623	36.2114425
	100.1534760	100.2012751
SN- 8	33.3728656	36.2120666
	100.0997511	100.1456766
SN- 9	33.3734448	36.2126657
	100.0460254	100.0900772
SN-10	33.3739999	36.2132399
	99.9922990	100.0344770
SN-11	33.3745305	36.2137891
	99.9385719	99.9788761
SN-12	33.3750376	36.2143133
	99.8848442	99.9232744
SN-13	33.3755203	36.2148126
	99.8311158	99.8676720
SN-14	33.3759783	36.2152869
	99.7773869	99.8120689
SN-15	33.3764133	36.2157363
	99.7236574	99.7564652
SN-16	33.3768235	36.2161607
	99.6699274	99.7008608
SN-17	33.3772097	36.2165602
	99.6161969	99.6452559
SN-18	33.3775717	36.2169347
	99.5624659	99.[illegible]

TABLE I (Con't)

SN-19	33.3779098 99.5037345	36.2172842 99.5340446
SN-20	33.3782234 99.4550027	36.2176088 99.4784382
SN-21	33.3785130 99.4012705	36.2179085 99.4225314
SN-22	33.3787765 99.3475360	36.2181830 99.3672242
SN-23	33.3790198 99.2938052	36.2184326 99.3116166
SN-24	33.3792371 99.2400721	36.2186573 99.2560087
SN-25	33.3794301 99.1863367	36.2188571 99.2004005
SN-26	33.3795991 99.1326051	36.2190319 99.1447921
SN-27	33.3797439 99.0788713	36.2191817 99.0891834
SN-28	33.3798646 99.0251373	36.2193065 99.0335746
SN-29	33.3799611 98.9714032	36.2194064 98.9779655
SN-30	33.3800335 98.9176691	36.2194813 98.9223564
SN-31	33.3800818 98.8639348	36.2195312 98.8667472
SN-32	33.3801059 98.8102005	36.2195562 98.8111380
SN-33	33.3801059 98.7564662	36.2195562 98.7555287
SN-34	33.3800818 98.7027319	36.2195312 98.6999194
SN-35	33.3800335 98.6489976	36.2194813 98.6443102
SN-36	33.3799611 98.5952634	36.2194064 98.5887011
SN-37	33.3798646 98.5415293	36.2193065 98.5330921
SN-38	33.3797439 98.4877954	36.2191817 98.4774833
SN-39	33.3795991 98.4340616	36.2190319 98.4218746

TABLE I (Con't)

SN-40	33.3794301 98.3803230	36.2188571 98.3652062
SN-41	33.3792371 98.3265946	36.2186573 98.3106580
SN-42	33.3790193 98.2728615	36.2184326 98.2550501
SN-43	33.3787785 98.2191286	36.2181830 98.1994425
SN-44	33.3785130 98.1653961	36.2179083 98.1438353
SN-45	33.3782234 98.1116639	36.2176085 98.0882285
SN-46	33.3779096 98.0579321	36.2172842 98.0326221
SN-47	33.3775717 98.0042007	36.2169347 97.9770161
SN-48	33.3772097 97.9504698	36.2165602 97.9214107
SN-49	33.3768235 97.8967393	36.2161607 97.8658058
SN-50	33.3764133 97.8430093	36.2157363 97.8102015
SN-51	33.3759788 97.7892798	36.2152869 97.7545978
SN-52	33.3755203 97.7355508	36.2148126 97.6989947
SN-53	33.3750376 97.6818225	36.2143133 97.6433923
SN-54	33.3745308 97.6280948	36.2137891 97.5877906
SN-55	33.3739999 97.5743677	36.2132399 97.5321896
SN-56	33.3734443 97.5206413	36.2126657 97.4765895
SN-57	33.3728656 97.4669156	36.2120666 97.4209901
SN-58	33.3722623 97.4131907	36.2114425 97.3653916
SN-59	33.3716349 97.3594663	36.2107935 97.3097939
SN-60	33.3709833 97.3057431	36.2101195 97.2541972

TABLE I (Con't)

SN-61	33.3703075 97.2520205	36.2094205 97.1986014
SN-62	33.3690078 97.1982956	36.2086966 97.1430066
SN-63	33.3688339 97.1445780	36.2079478 97.0374129
SN-64	33.3681358 97.0908581	36.2071740 97.0318201

TABLE I (Con't)

WAY POINTS FOR GGSS OKLAHOMA SURVEY AREA-315KM SIDES

WEST to EAST TRACKS (written from south-west most corner)

TRACK	WEST: LATITUDE LONGITUDE	EAST: LATITUDE LONGITUDE
WE- 1	33.3681358 100.4758066	33.3681358 97.0908581
WE- 2	33.4132109 100.4766826	33.4132109 97.0899841
WE- 3	33.4582356 100.4775586	33.4582856 97.0891081
WE- 4	33.5033600 100.4784365	33.5033600 97.0882302
WE- 5	33.5484340 100.4793164	33.5484340 97.0873503
WE- 6	33.5935076 100.4801982	33.5935076 97.0864684
WE- 7	33.6385810 100.4810820	33.6385810 97.0855846
WE- 8	33.6836539 100.4819675	33.6836539 97.0846989
WE- 9	33.7287265 100.4828556	33.7287265 97.0838111
WE-10	33.7737989 100.4837453	33.7737989 97.0829214
WE-11	33.8188707 100.4846370	33.8188707 97.0820297
WE-12	33.8639423 100.4855307	33.8639423 97.0811360
WE-13	33.9090135 100.4864263	33.9090135 97.0802403
WE-14	33.9540844 100.4873240	33.9540844 97.0793427
WE-15	33.9991549 100.4882237	33.9991549 97.0784430
WE-16	34.0442251 100.4891253	34.0442251 97.0775413
WE-17	34.0892949 100.4900290	34.0892949 97.0766376
WE-18	34.1343643 100.4909347	34.1343643 97.0757320

TABLE I (Con't)

WE-19	34.1794334	34.1794334
	100.4915424	97.0748243
WE-20	34.2245022	34.2245022
	100.4927521	97.0739146
WE-21	34.2695706	34.2695706
	100.4936639	97.0730025
WE-22	34.3146386	34.3146386
	100.4945776	97.0720890
WE-23	34.3597063	34.3597063
	100.4954934	97.0711732
WE-24	34.4047736	34.4047736
	100.4964113	97.0702554
WE-25	34.4498406	34.4498406
	100.4973311	97.0693355
WE-26	34.4949072	34.4949072
	100.4982530	97.0684136
WE-27	34.5399735	34.5399735
	100.4991770	97.0674896
WE-28	34.5850394	34.5850394
	100.5001030	97.0665636
WE-29	34.6301050	34.6301050
	100.5010311	97.0656355
WE-30	34.6751702	34.6751702
	100.5019613	97.0647054
WE-31	34.7202351	34.7202351
	100.5028935	97.0637732
WE-32	34.7652996	34.7652996
	100.5038278	97.0628389
WE-33	34.8103637	34.8103637
	100.5047642	97.0619025
WE-34	34.8554275	34.8554275
	100.5057026	97.0609641
WE-35	34.9004909	34.9004909
	100.5066431	97.0600235
WE-36	34.9455540	34.9455540
	100.5075857	97.0590809
WE-37	34.9906167	34.9906167
	100.5085303	97.0581362
WE-38	35.0356790	35.0356790
	100.5094773	97.0571894
WE-39	35.0807410	35.0807410
	100.5104262	97.0562405

TABLE I (Con't)

WE-40	35.1258027	35.1258027
	100.5113772	97.0552895
WE-41	35.1708640	35.1708640
	100.5123303	97.0543363
WE-42	35.2159249	35.2159249
	100.5132856	97.0533811
WE-43	35.2609855	35.2609855
	100.5142430	97.0524237
WE-44	35.3060457	35.3060457
	100.5152025	97.0514642
WE-45	35.3511055	35.3511055
	100.5161641	97.0505026
WE-46	35.3961650	35.3961650
	100.5171279	97.0495385
WE-47	35.4412241	35.4412241
	100.5180938	97.0485729
WE-48	35.4862829	35.4862829
	100.5190618	97.0476046
WE-49	35.5313413	35.5313413
	100.5200320	97.0466346
WE-50	35.5763993	35.5763993
	100.5210044	97.0456623
WE-51	35.6214570	35.6214570
	100.5219789	97.0446877
WE-52	35.6665144	35.6665144
	100.5229556	97.0437111
WE-53	35.7115713	35.7115713
	100.5239345	97.0427322
WE-54	35.7566279	35.7566279
	100.5249155	97.0417512
WE-55	35.8016842	35.8016842
	100.5258987	97.0407680
WE-56	35.8467400	35.8467400
	100.5268841	97.0397826
WE-57	35.8917956	35.8917956
	100.5278717	97.0387950
WE-58	35.9368507	35.9368507
	100.5288615	97.0378052
WE-59	35.9819055	35.9819055
	100.5298535	97.0368132
WE-60	36.0269599	36.0269599
	100.5308476	97.0358190

TABLE I (Con't)

WE-61	36.0720140	36.0720140
	100.5316440	97.0346236
WE-62	36.1170677	36.1170677
	100.5326426	97.0333240
WE-63	36.1621210	36.1621210
	100.5336435	97.0326233
WE-64	36.2071740	36.2071740
	100.5346465	97.0318201

TABLE 2

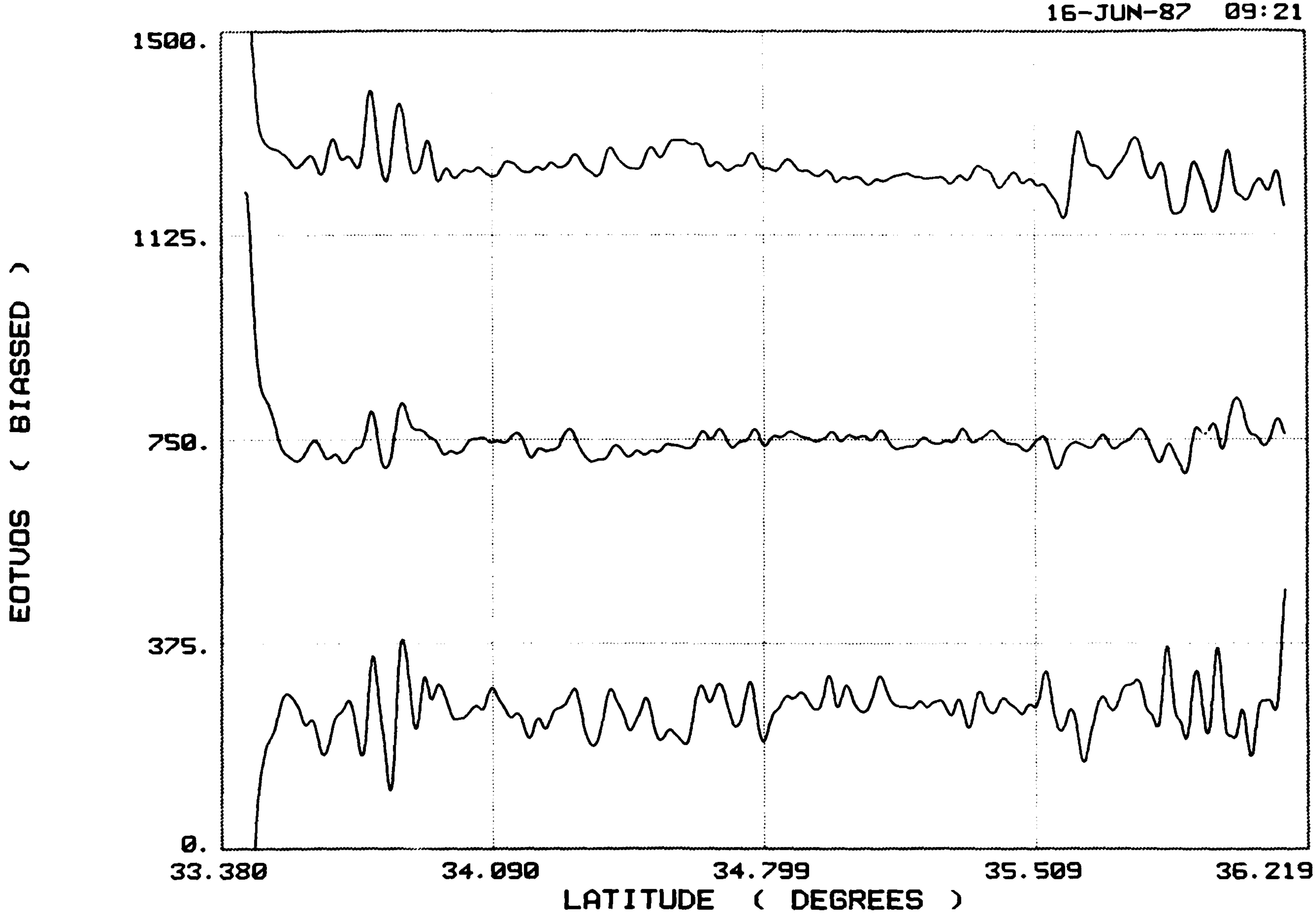
GGSS Oklahoma Survey Tracks (Airborne)

The tracks extend 0 - 320Km where 0 is the most westerly or southerly point. Thus, the listed Central Latitude/Longitude is 160Km along track.

E/W Track Number	Central Lat/Long	Best Sections (Km)
7	33.6506/-98.8103	All
22	34.3267/-98.8105	160 - 320
26	34.5070/-98.8106	40 - 320
47	35.4535/-98.8109	All
49	35.5436/-98.8109	20 - 235
53	35.7239/-98.8110	25 - 265
55	35.8140/-98.8110	70 - 320
60	36.0393/-98.8111	120 - 265
61	36.0844/-98.8111	All

N/S Track Number	Central Lat/Long	Best Sections (Km)
28	34.7772/-99.0291	35 - 250
30	34.7774/-98.9200	All
35	34.7774/-98.6468	0 - 200
39	34.7769/-98.4283	All
41	34.7766/-98.3190	0 - 300
42	34.7764/-98.2644	0 - 280
43	34.7761/-98.2098	All
44	34.7758/-98.1552	85 - 300
46	34.7752/-98.0459	All
48	34.7745/-97.9367	All
51	34.7733/-97.7728	All
53	34.7723/-97.6636	All
55	34.7713/-97.5544	All
61	34.7675/-97.2267	0 - 200

FIGURE 3



FLIGHT #1 NS T28 GI123 (COMPENSATED)

5417

FIGURE 4

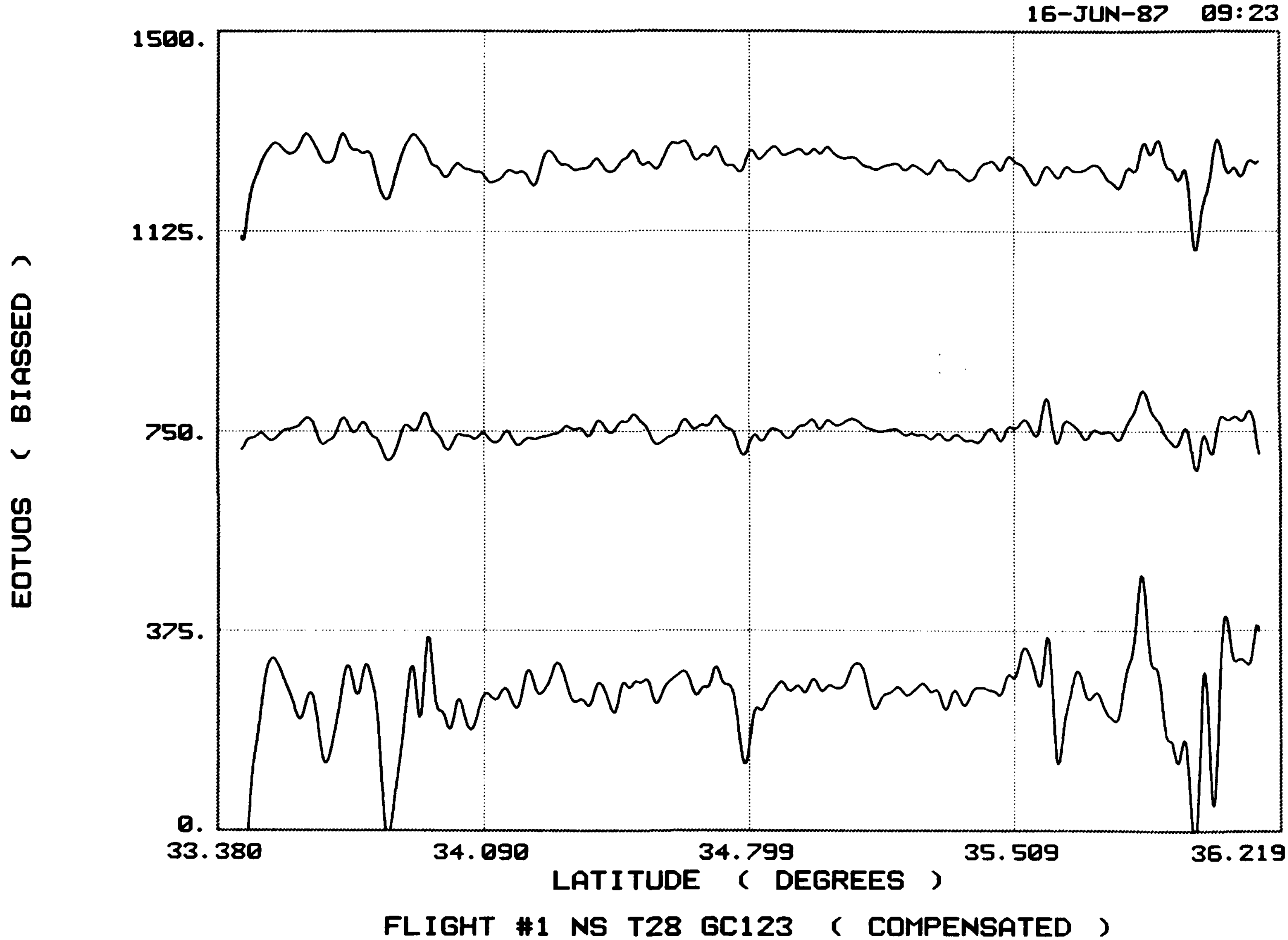
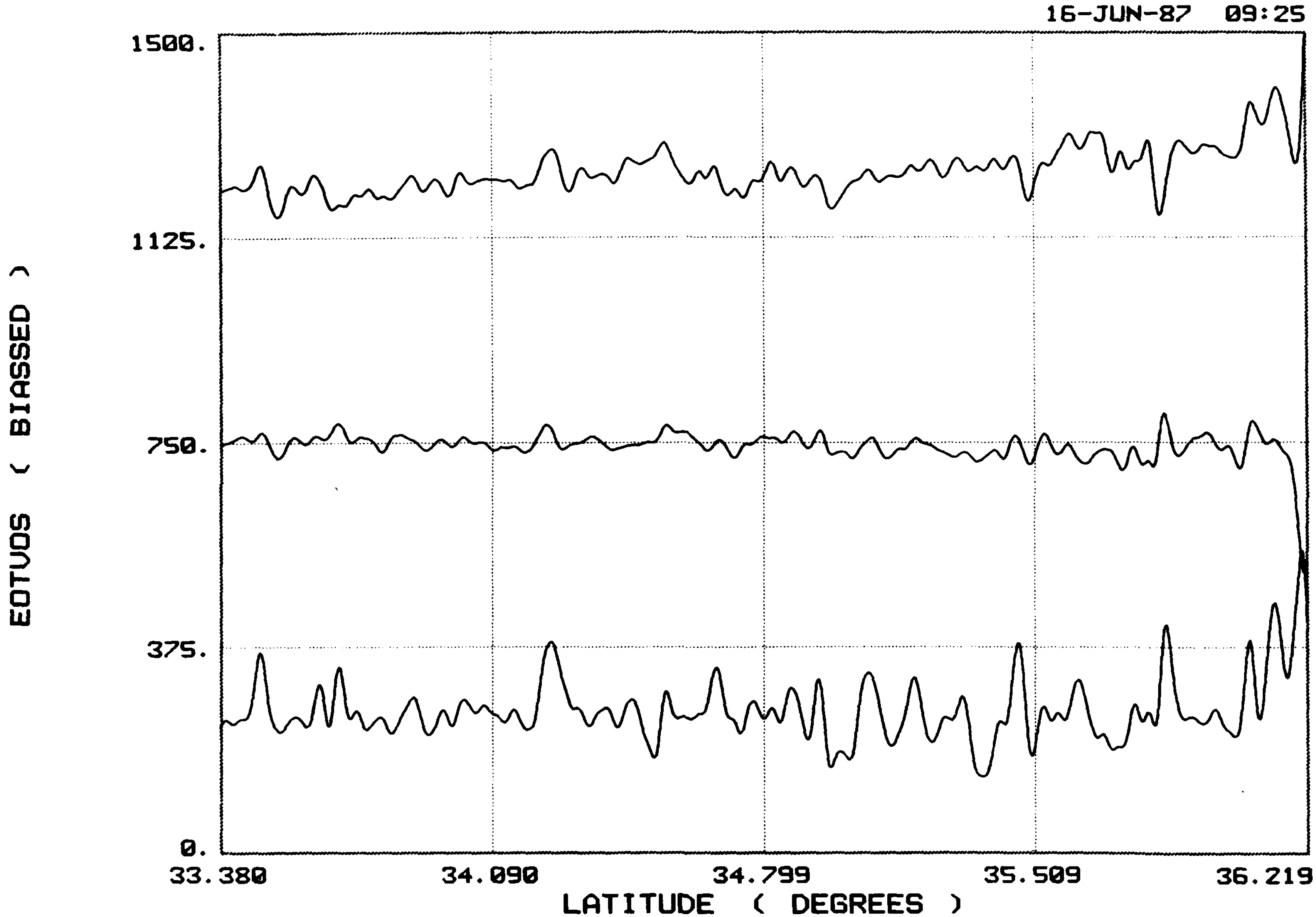
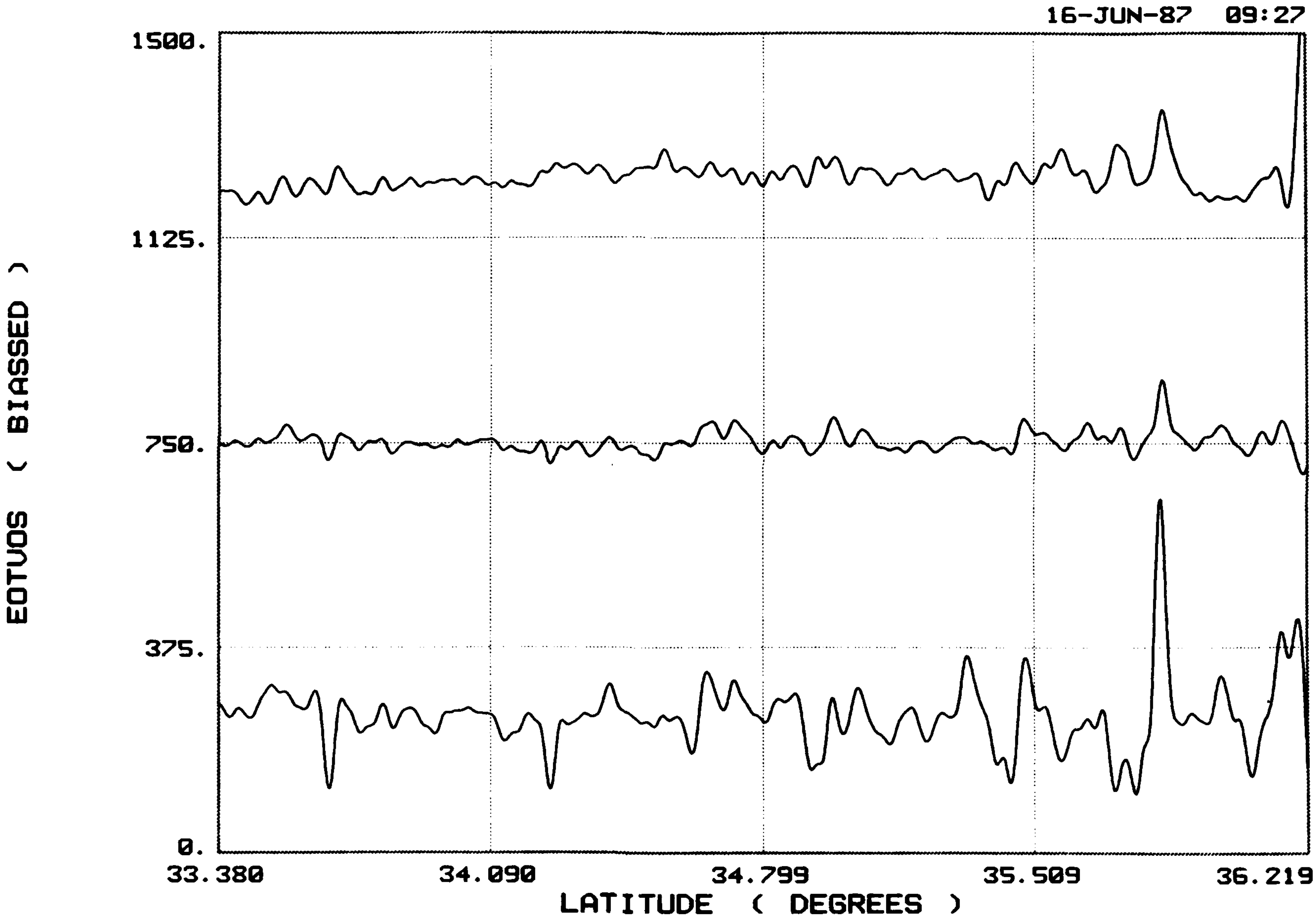

16-JUN-87 09:23
1500.
1125.
750.
375.
0.
EOTVOS (BIASSED)
33.380
34.090
34.799
35.509
36.219
LATITUDE (DEGREES)
FLIGHT #1 NS T28 GC123 (COMPENSATED)

FIGURE 5



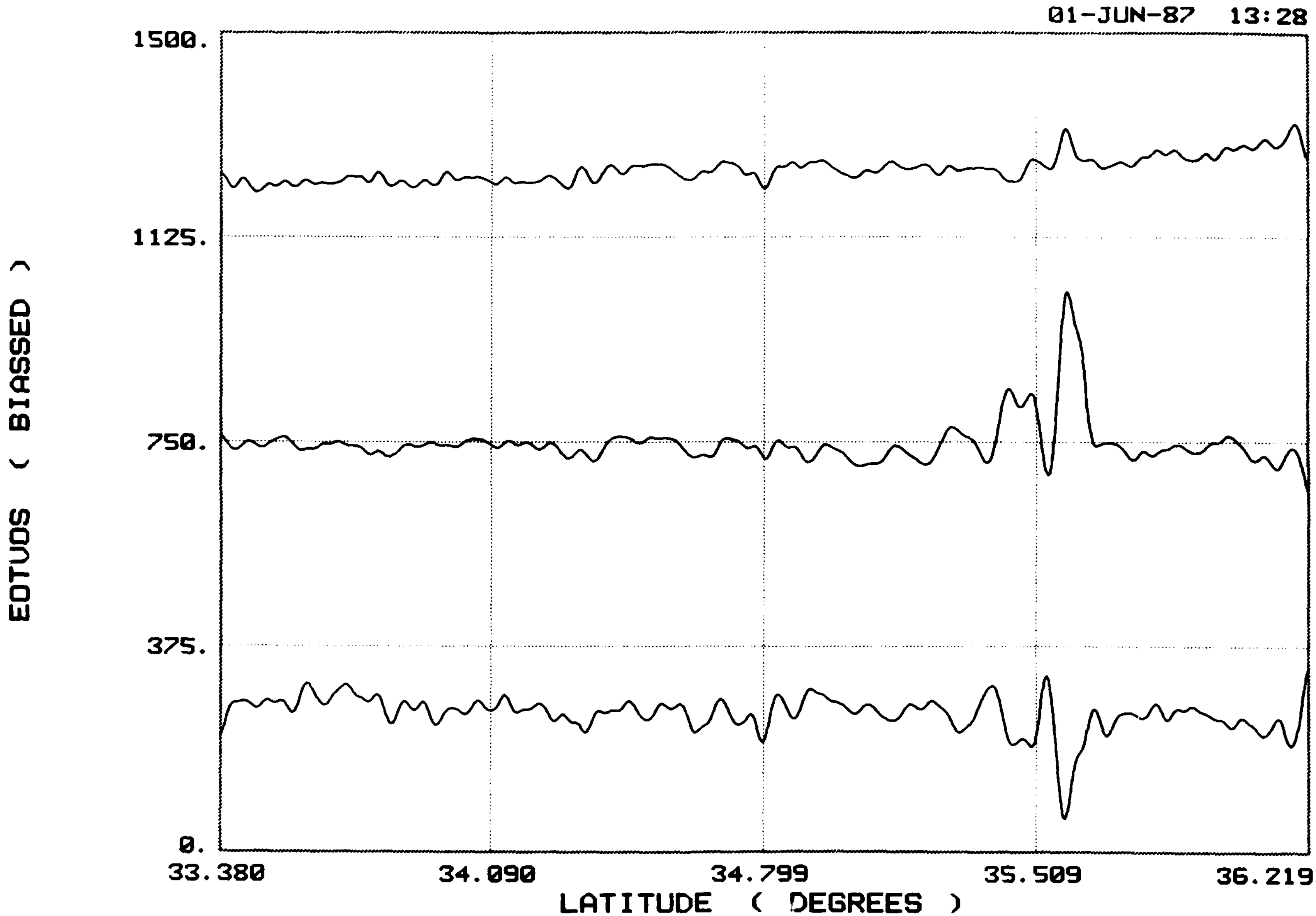
FLIGHT #1 NS T30 GI123 (COMPENSATED)

FIGURE 6



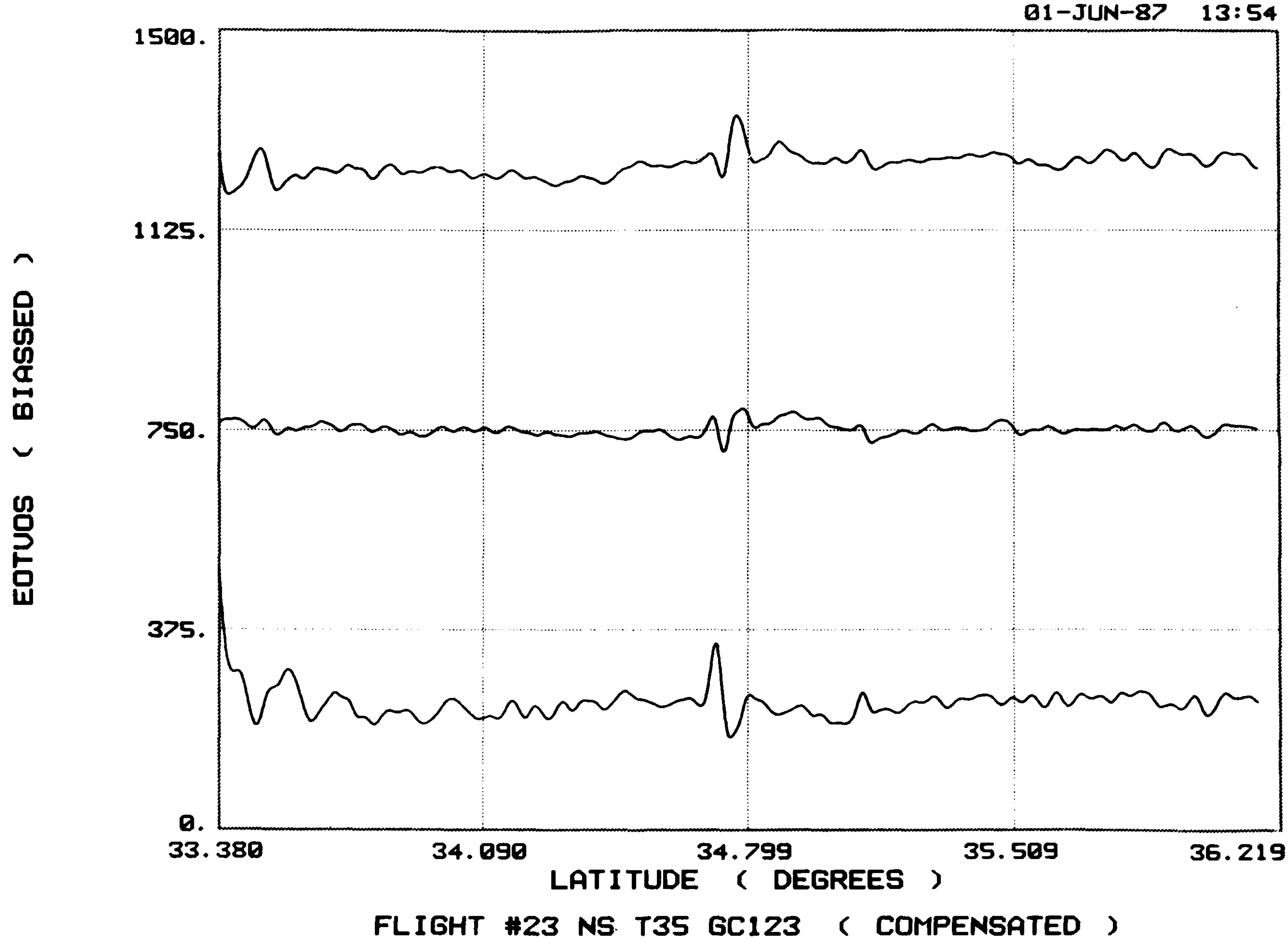
FLIGHT 31 NS T30 GC123 (COMPEMNSATED)

FIGURE 7



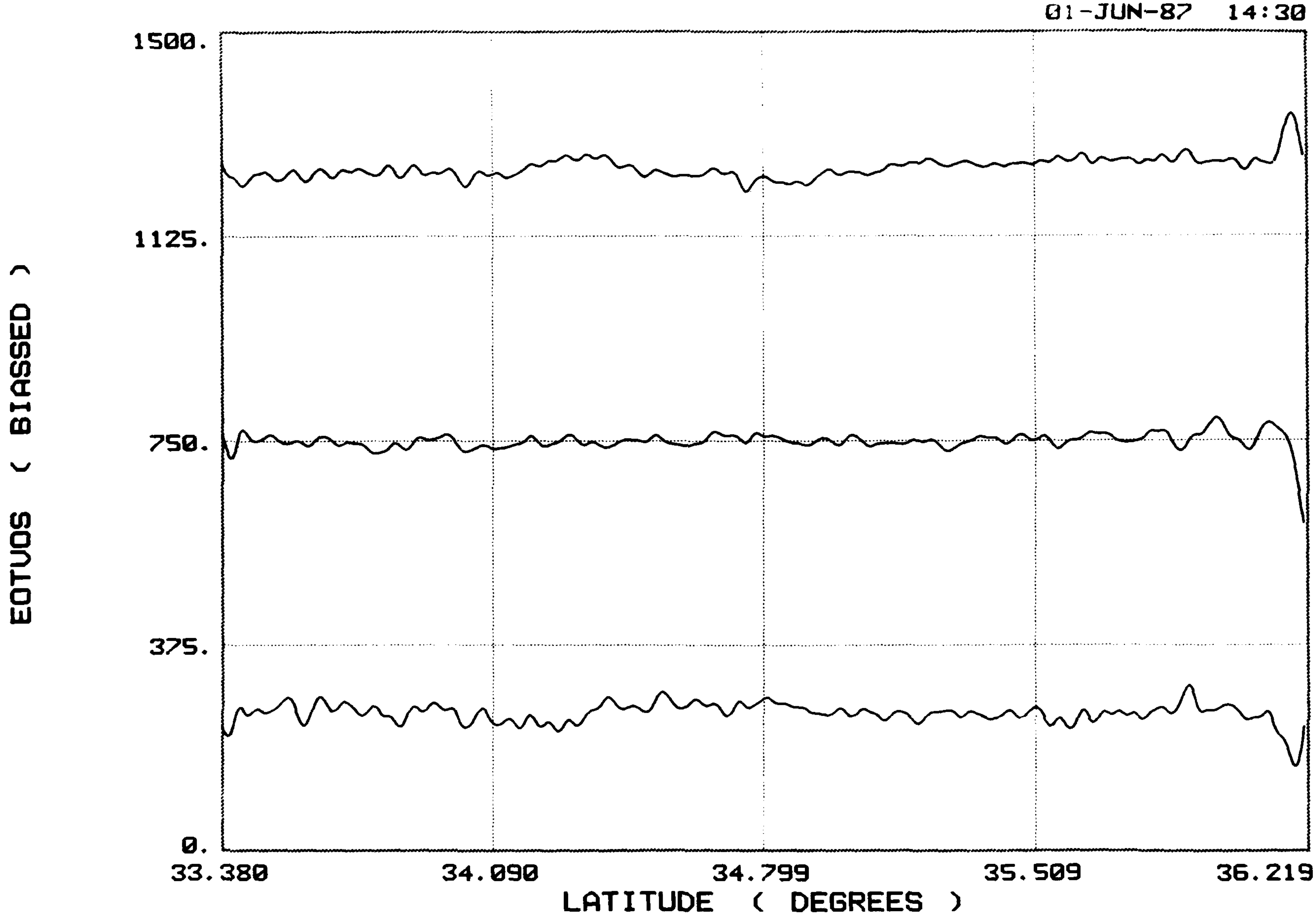
FLIGHT #23 NS T35 GI123 (COMPENSATED)

FIGURE 8



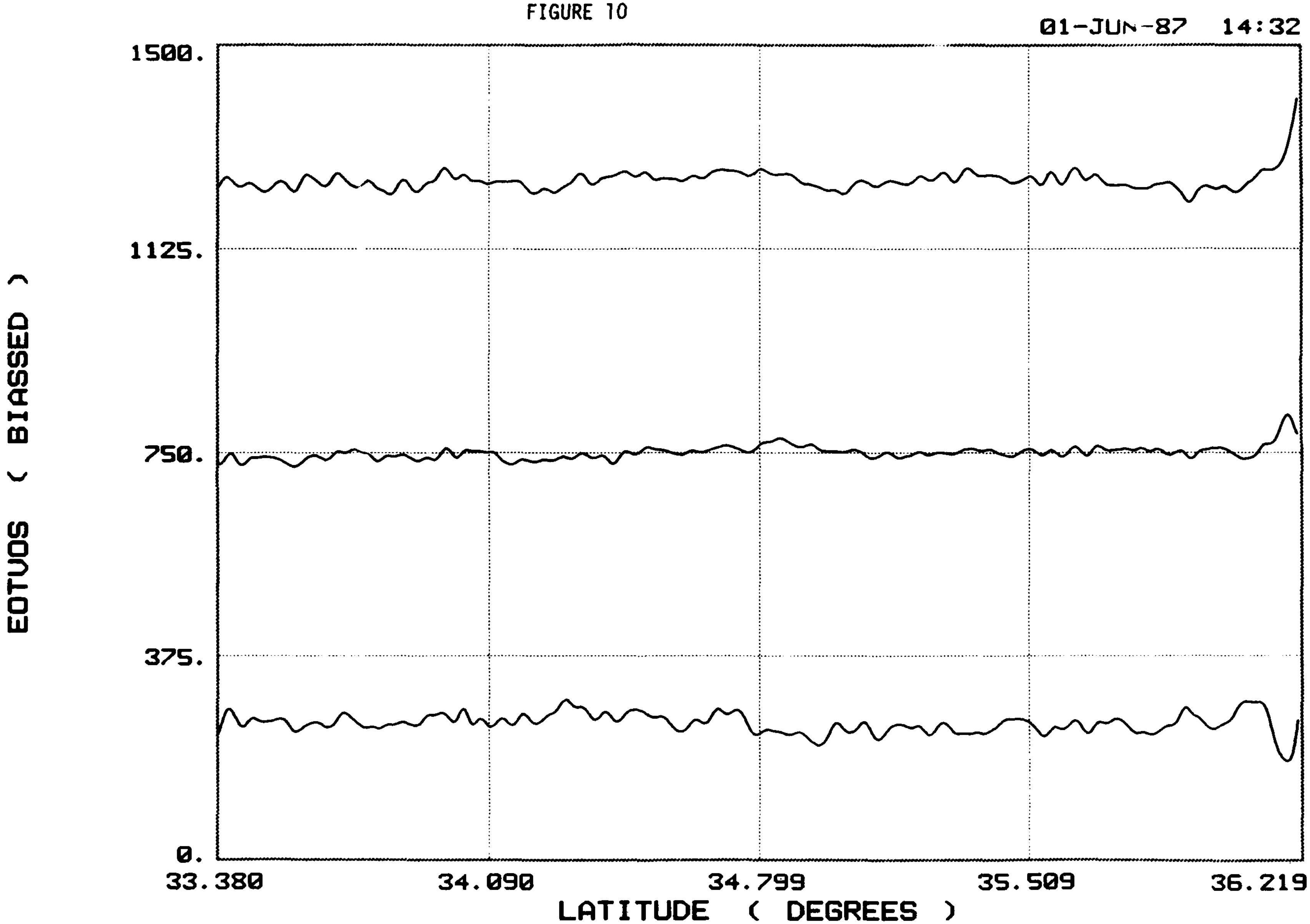
01-JUN-87 13:54
1500.
1125.
750.
375.
0.
33.380
34.090
34.799
35.509
36.219
LATITUDE (DEGREES)
EOTVOS (BIASSED)
FLIGHT #23 NS T35 GC123 (COMPENSATED)

FIGURE 9



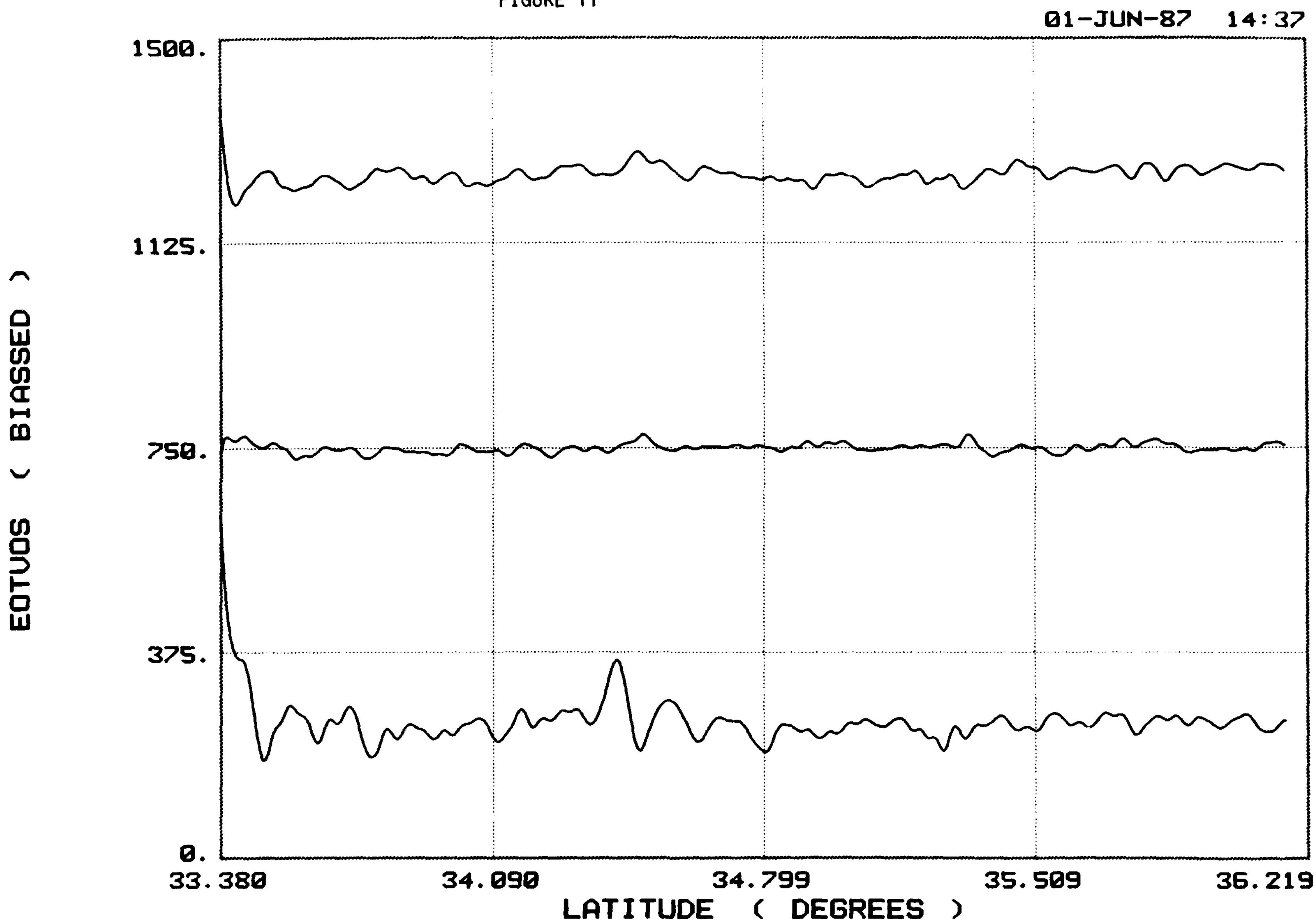
FLIGHT #23 NS T39 GI123 (COMPENSATED)

FIGURE 10



FLIGHT #23 NS T39 GC123 (COMPENSATED)

FIGURE 11



FLIGHT #23 NS T41 GC123 (COMPENSATED)

FIGURE 12

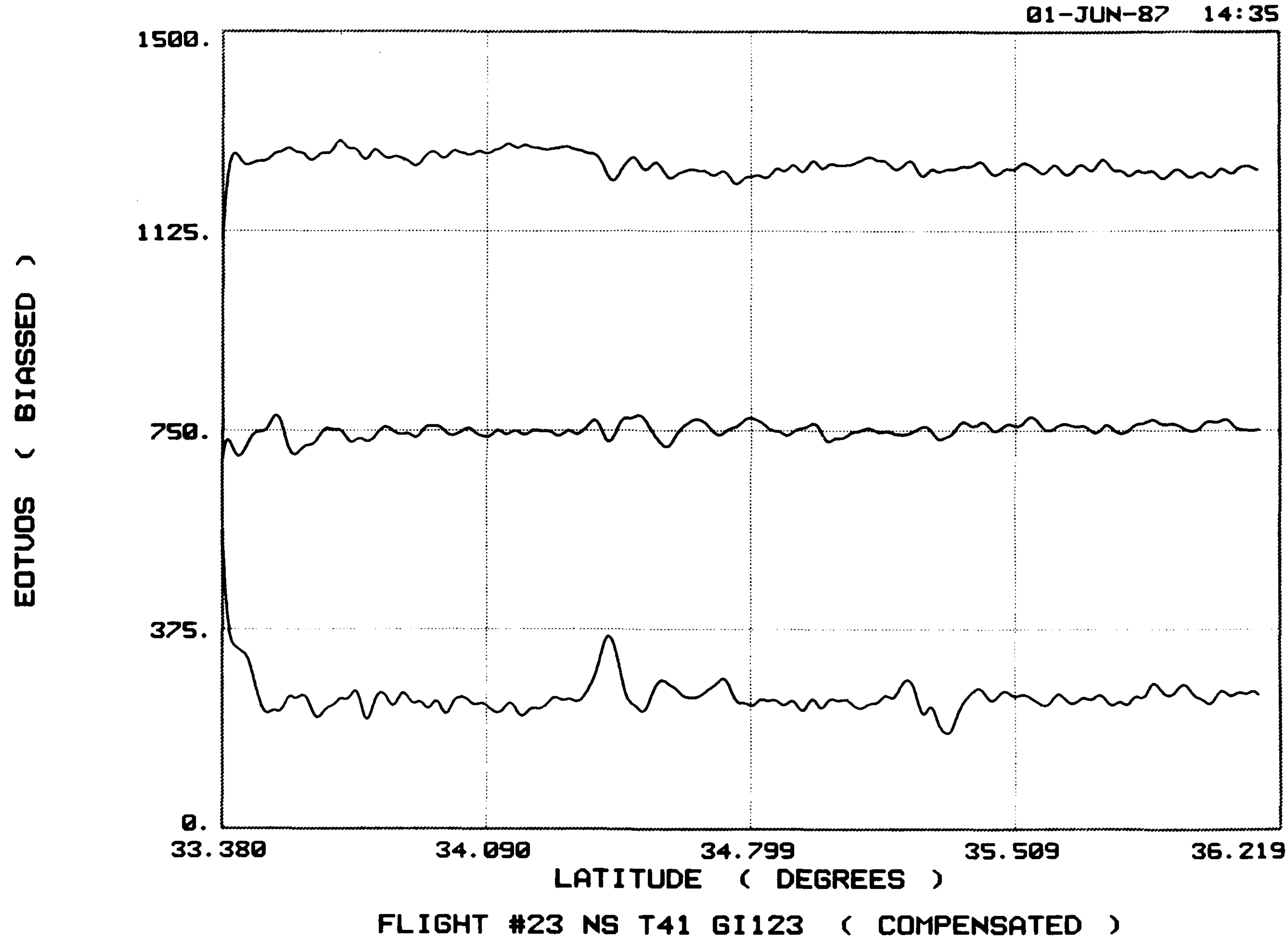
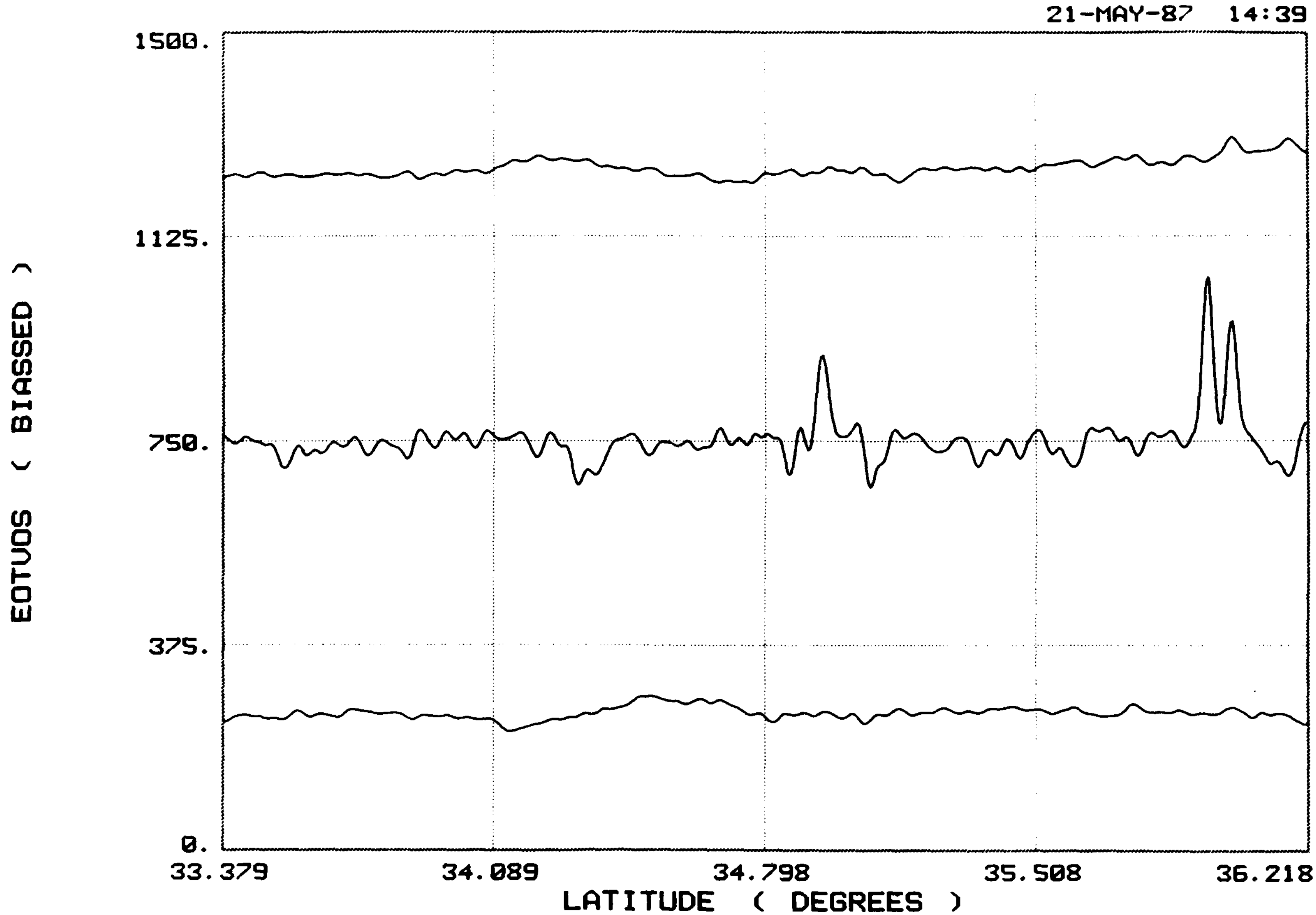

01-JUN-87 14:35
1500.
1125.
750.
375.
0.
EOTVOS (BIASSED)
33.380
34.090
34.799
35.509
36.219
LATITUDE (DEGREES)
FLIGHT #23 NS T41 GI123 (COMPENSATED)

FIGURE 13



FLIGHT #13 NS T42 GI123 (COMPENSATED)

FIGURE 14

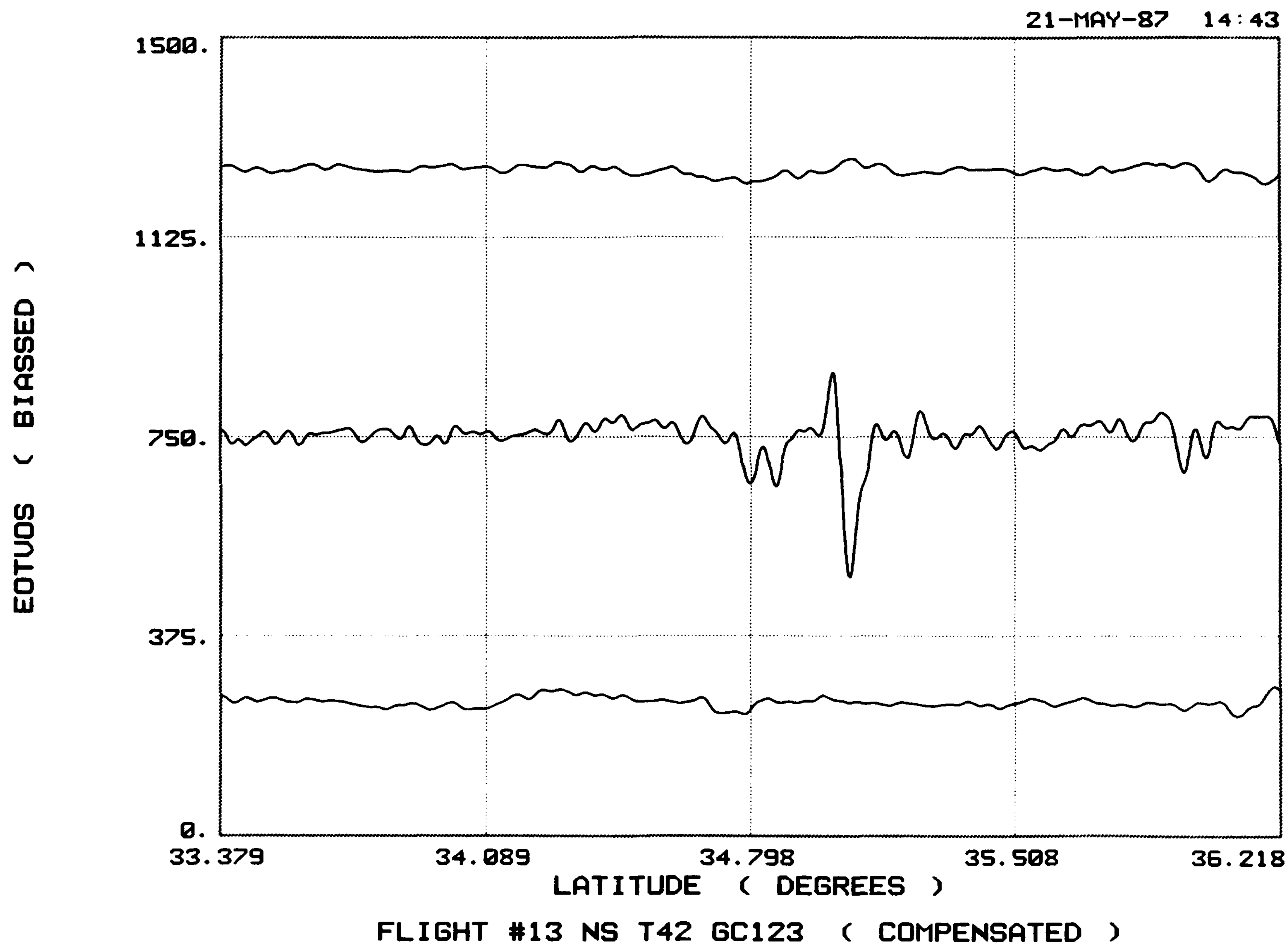

21-MAY-87 14:43
1500.
1125.
750.
375.
0.
EOTVOS (BIASSED)
33.379
34.089
34.798
35.508
36.218
LATITUDE (DEGREES)
FLIGHT #13 NS T42 GC123 (COMPENSATED)

FIGURE 15

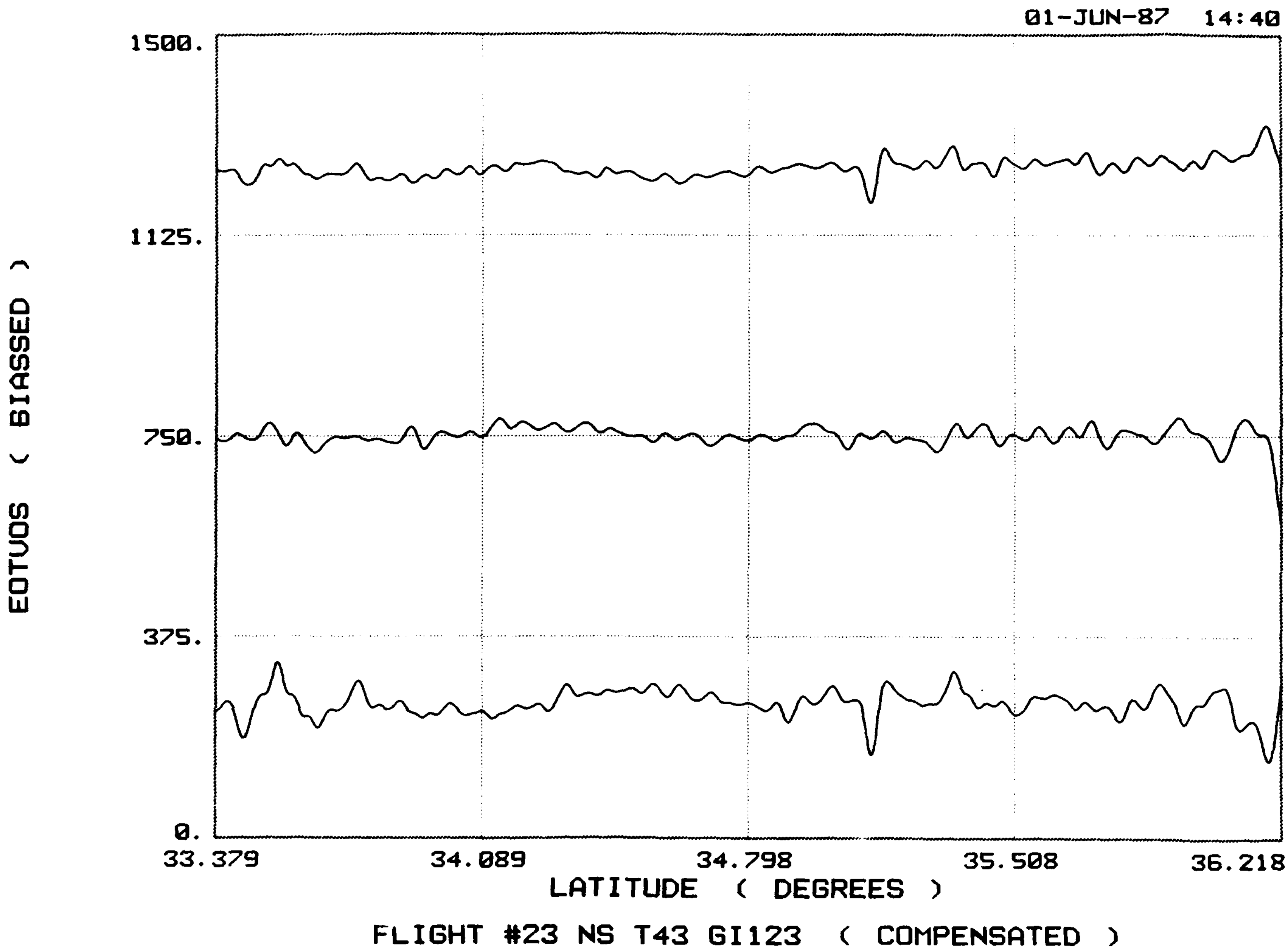
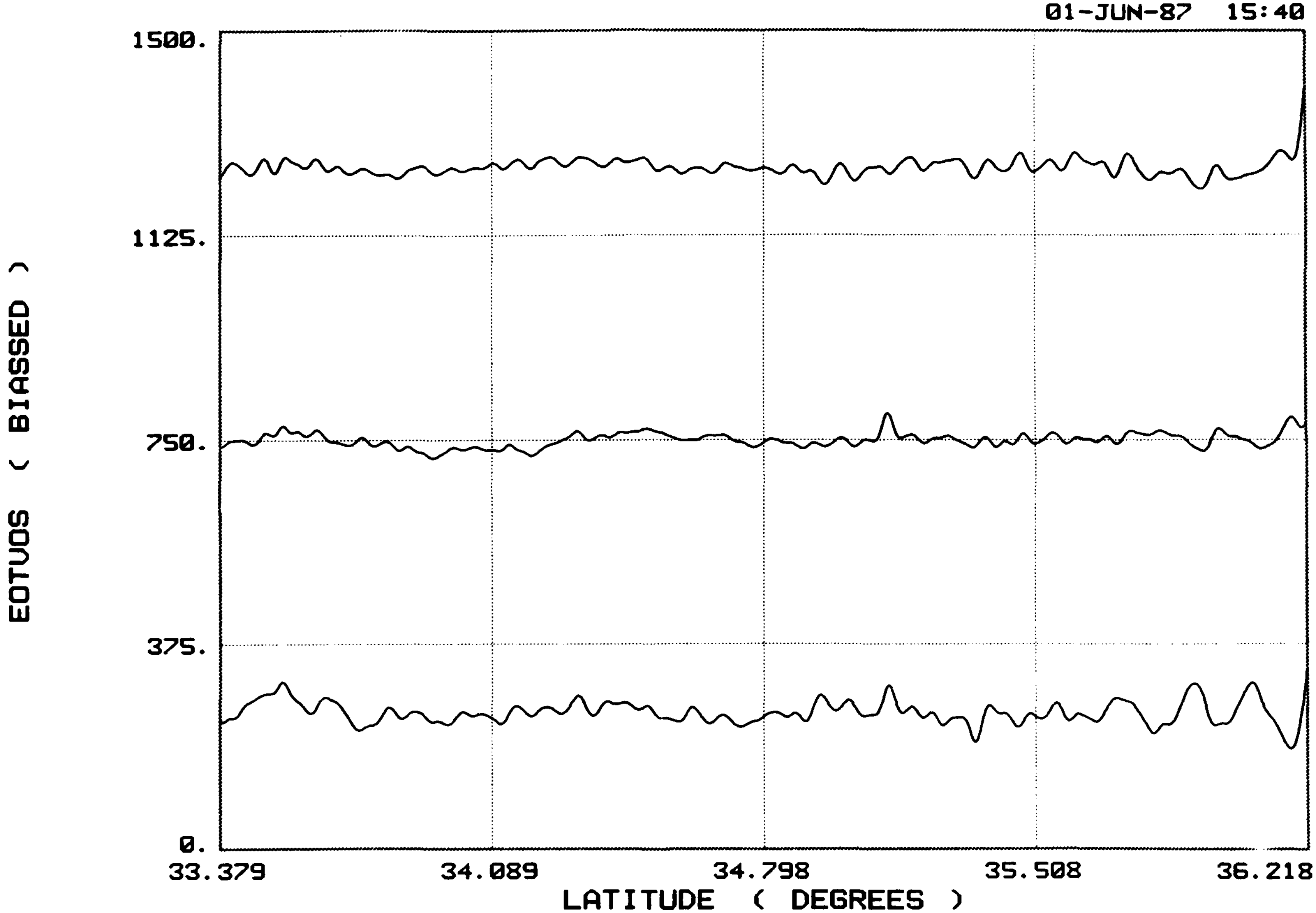
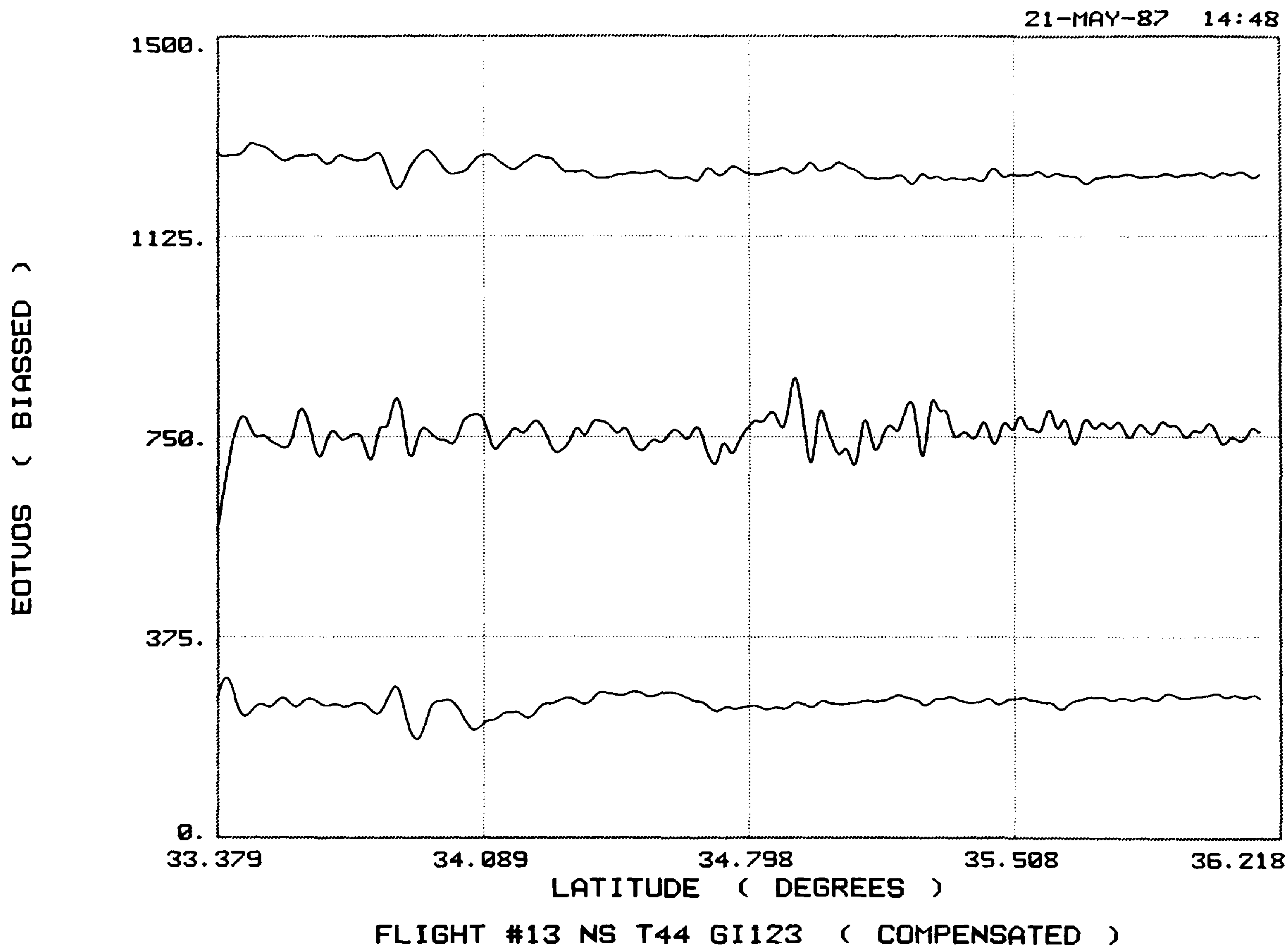

01-JUN-87 14:40
1500.
1125.
750.
375.
0.
EOTVOS (BIASSED)
33.379
34.089
34.798
35.508
36.218
LATITUDE (DEGREES)
FLIGHT #23 NS T43 GI123 (COMPENSATED)

FIGURE 16



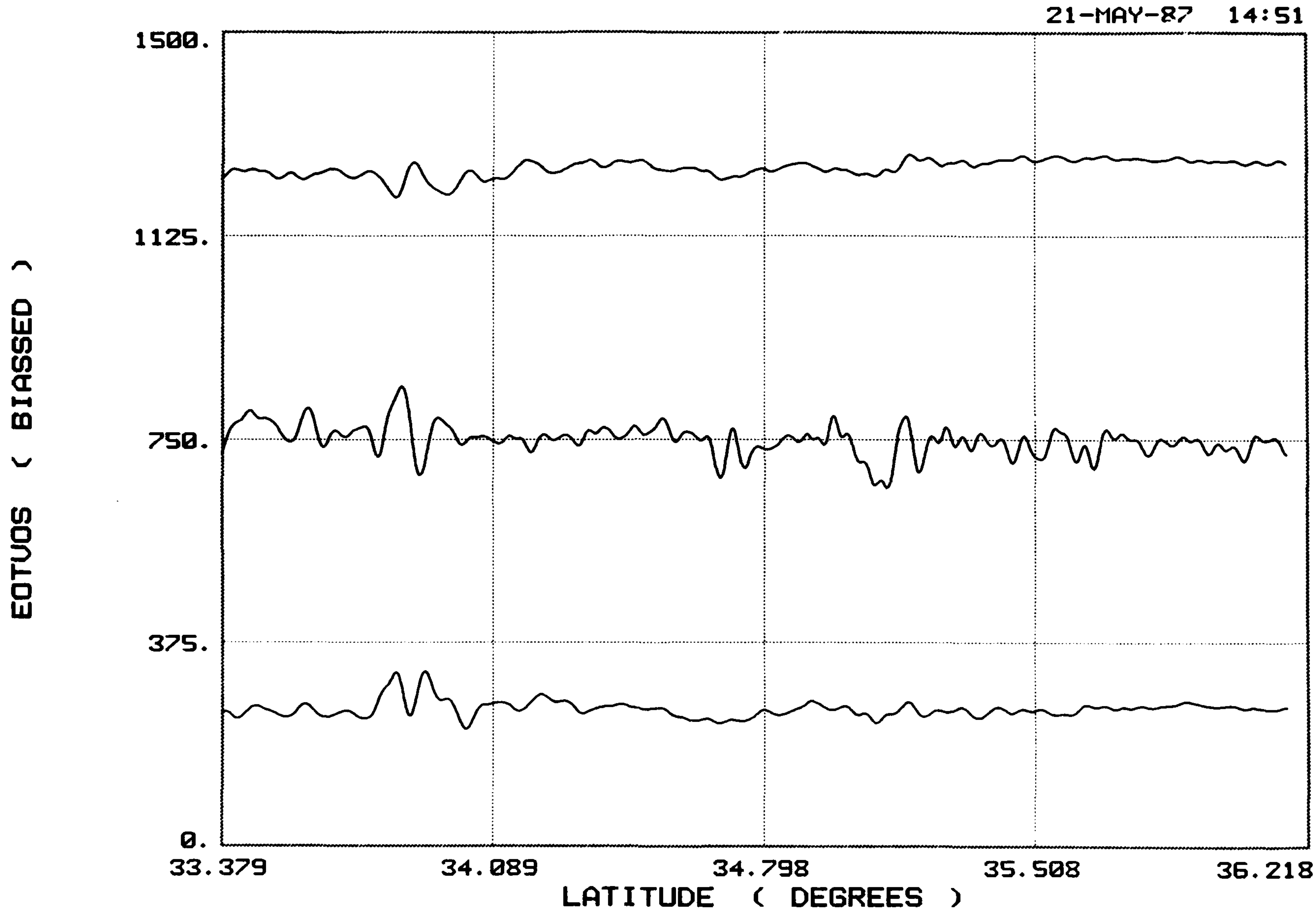
FLIGHT #23 NS T43 GC123 (COMPENSATED)

FIGURE 17



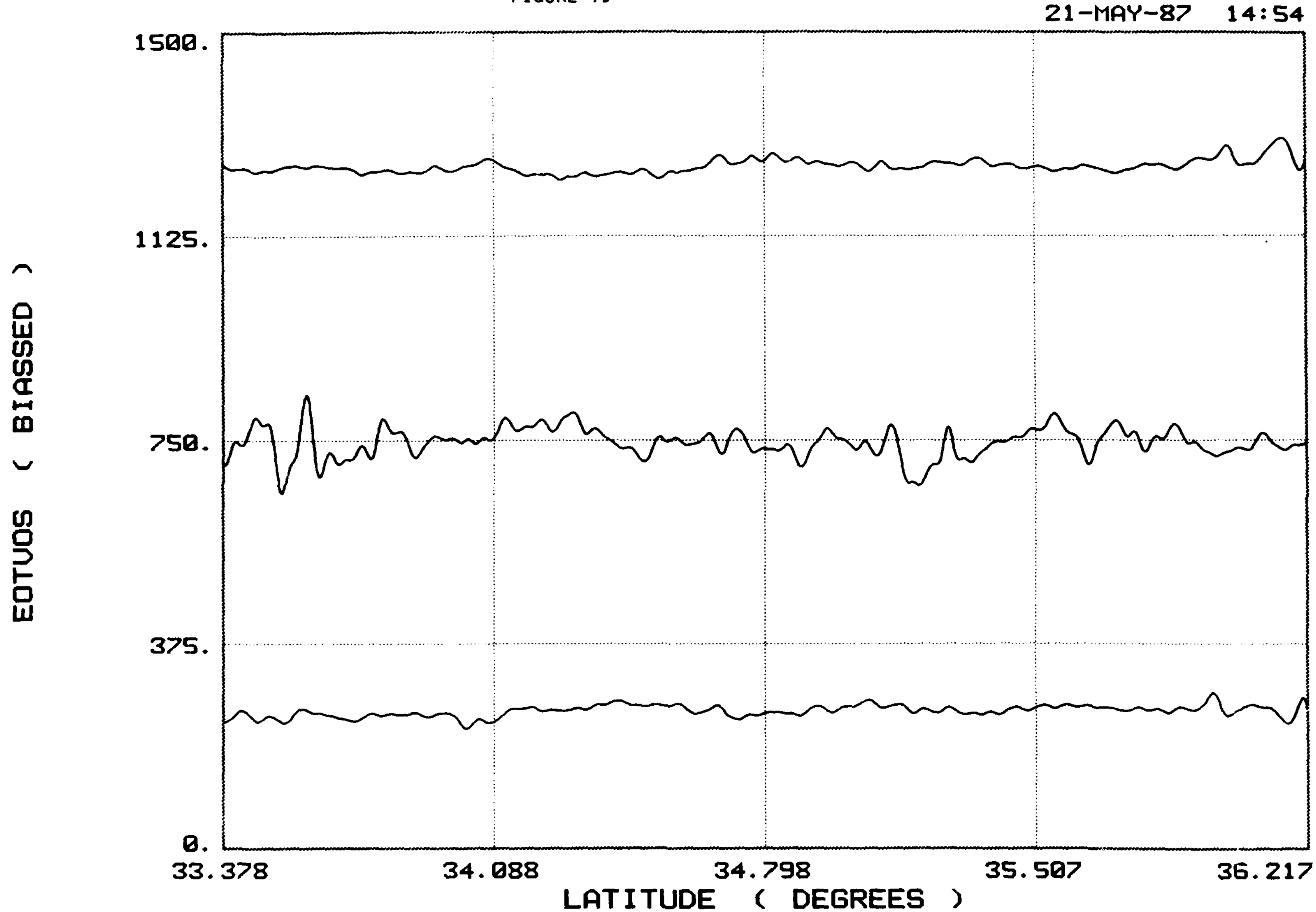
21-MAY-87 14:48
1500.
1125.
750.
375.
0.
EOTVOS (BIASSED)
33.379
34.089
34.798
35.508
36.218
LATITUDE (DEGREES)
FLIGHT #13 NS T44 GI123 (COMPENSATED)

FIGURE 18



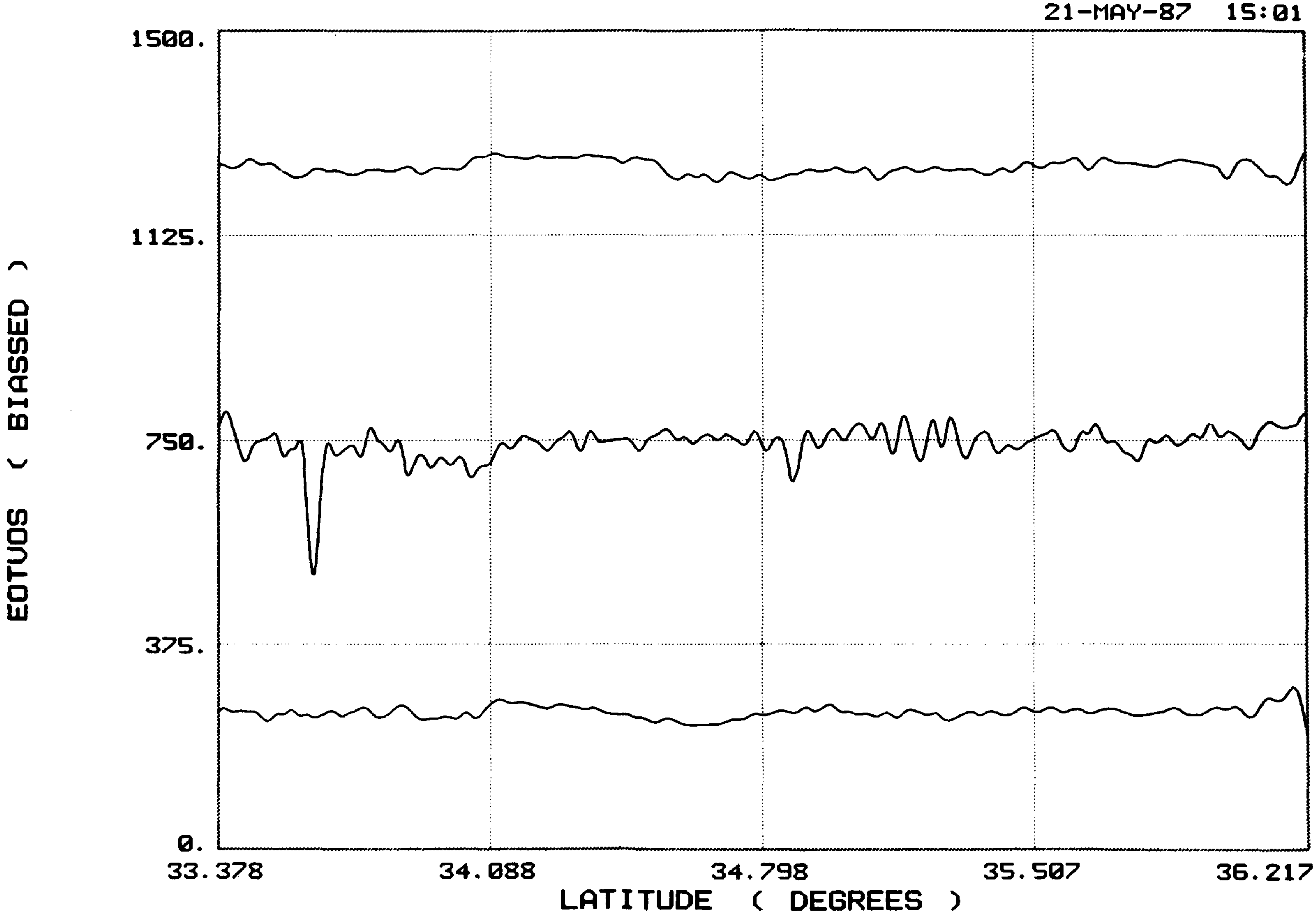
FLIGHT #13 NS T44 GC123 (COMPENSATED)

FIGURE 19



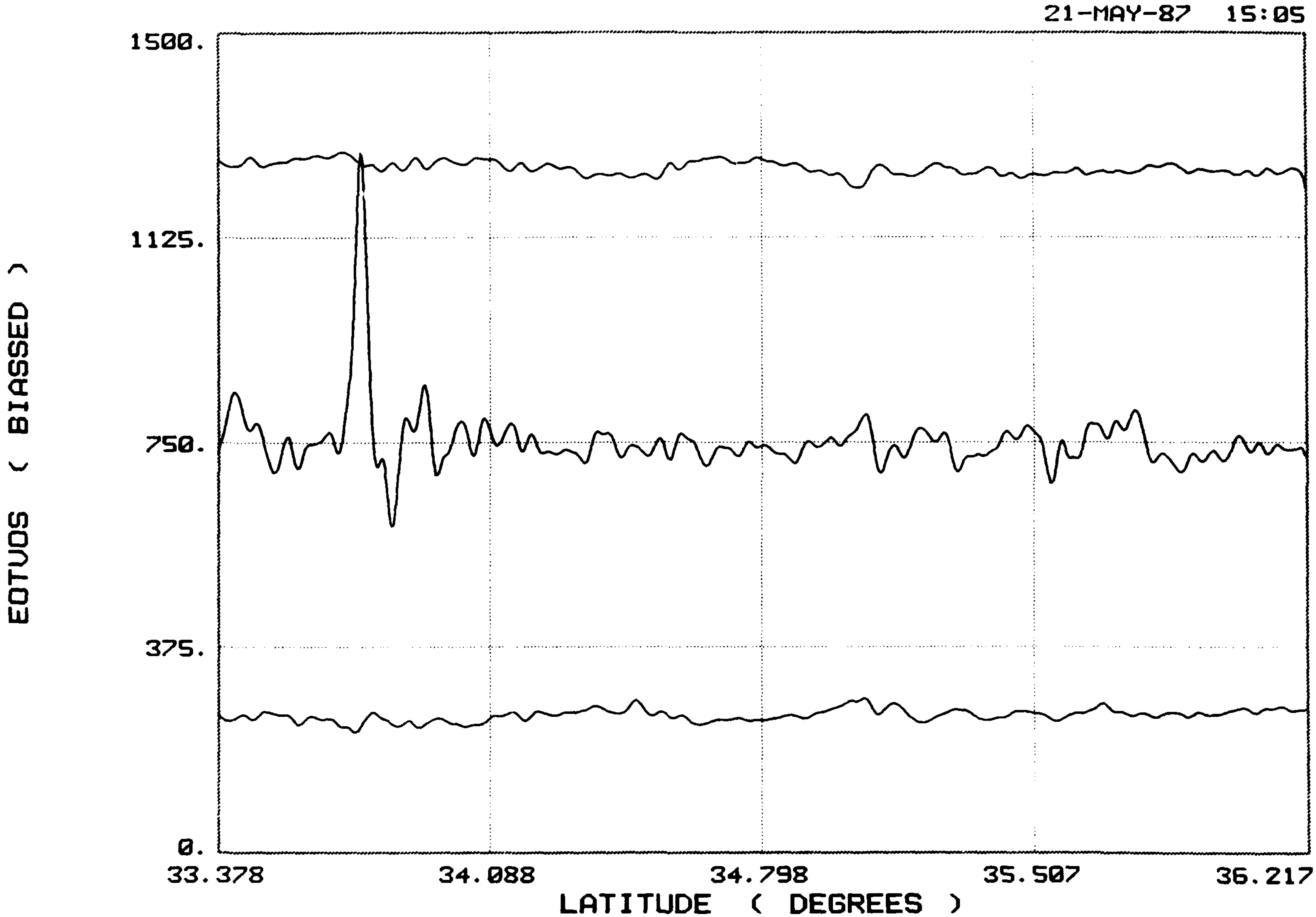
FLIGHT #13 NS T46 GI123 (COMPENSATED)

FIGURE 20



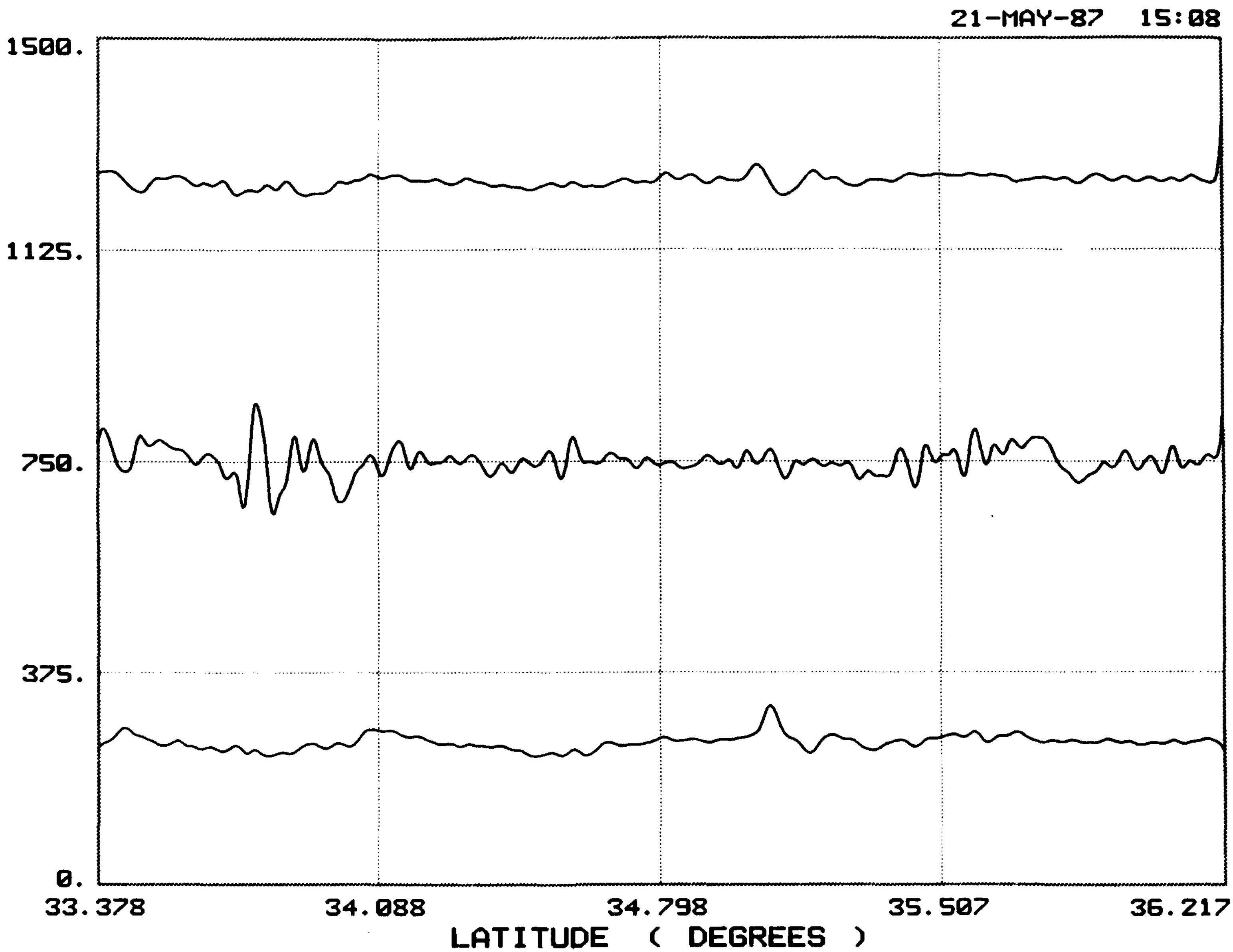
FLIGHT #13 NS T46 GC123 (COMPENSATED)

FIGURE 21



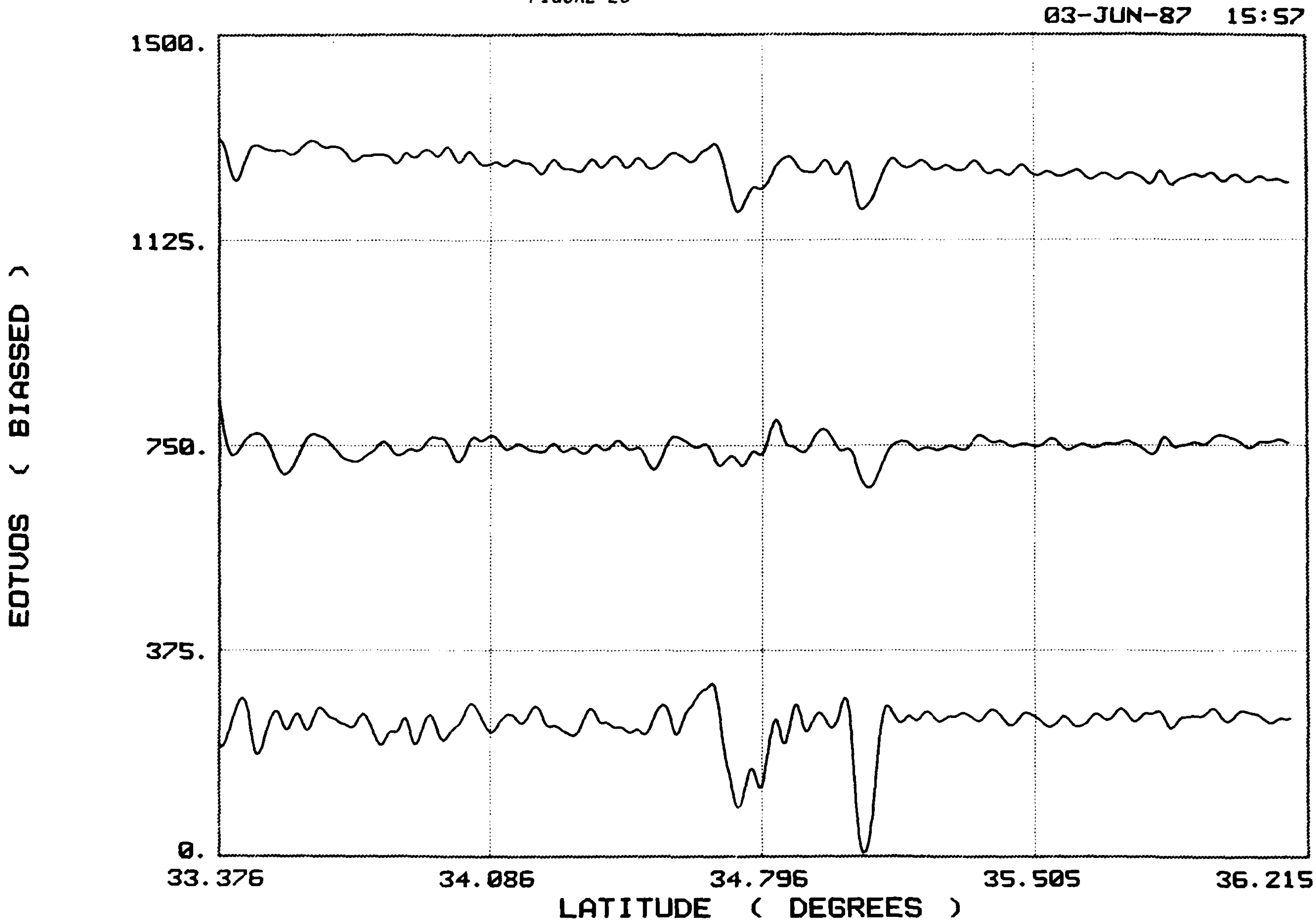
FLIGHT #13 NS T48 GI123 (COMPENSATED)

FIGURE 22



FLIGHT #13 NS T48 GC123 (COMPENSATED)

FIGURE 23



FLIGHT #25 NS TS1 GI123 (COMPENSATED)

FIGURE 24

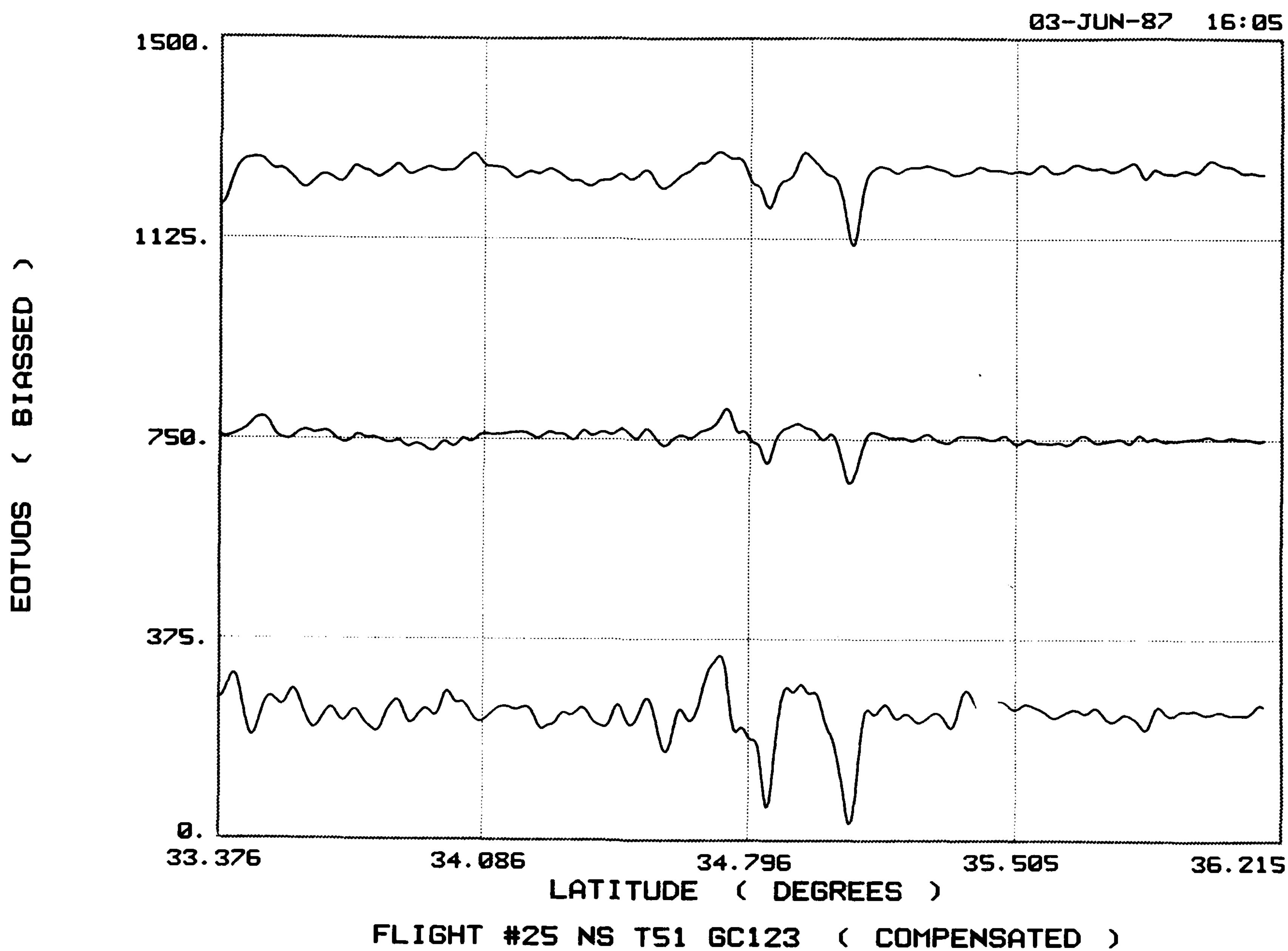
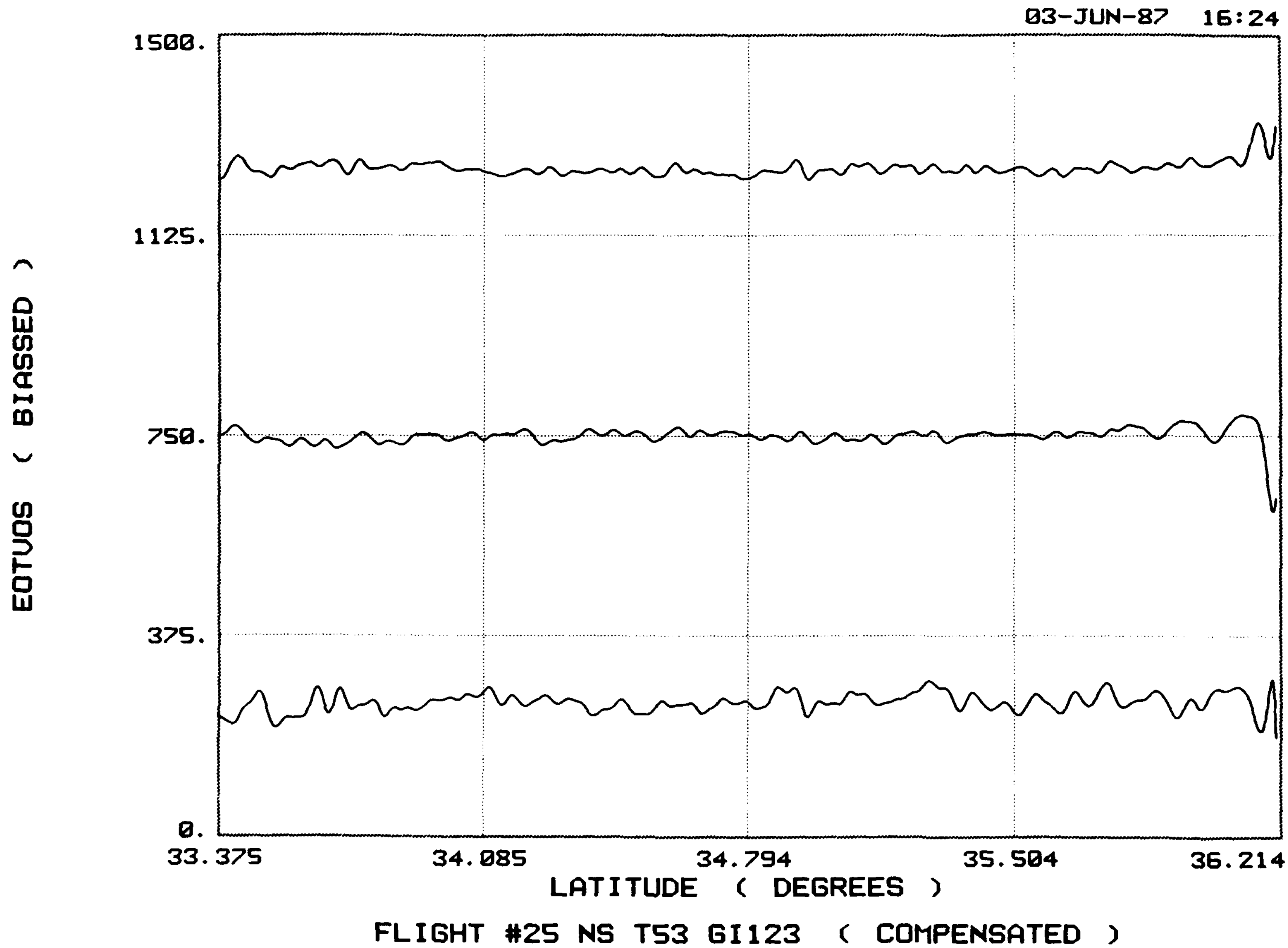
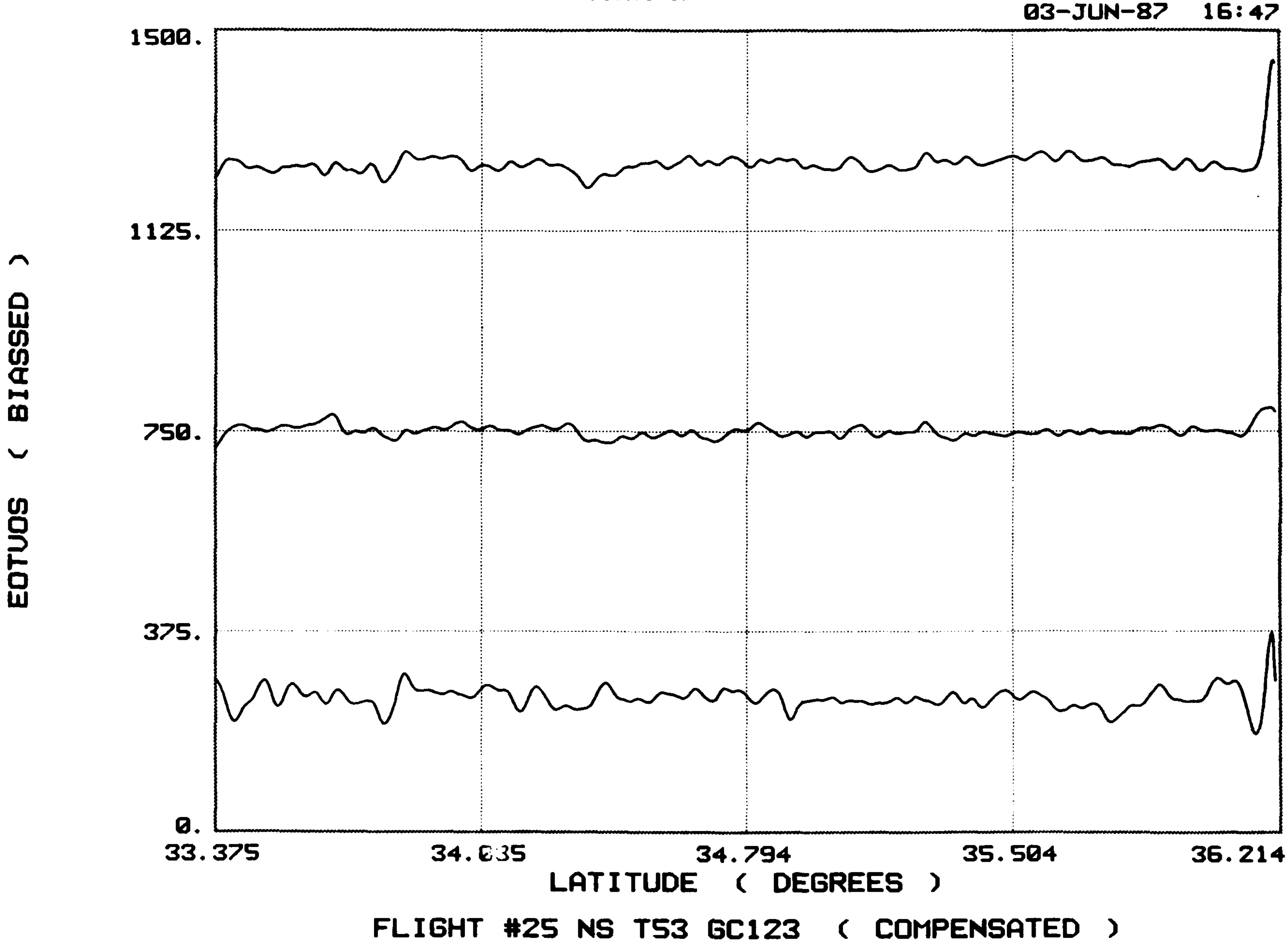

03-JUN-87 16:05
1500.
1125.
750.
375.
0.
EOTVOS (BIASSED)
33.376
34.086
34.796
35.505
36.215
LATITUDE (DEGREES)
FLIGHT #25 NS T51 GC123 (COMPENSATED)

FIGURE 25



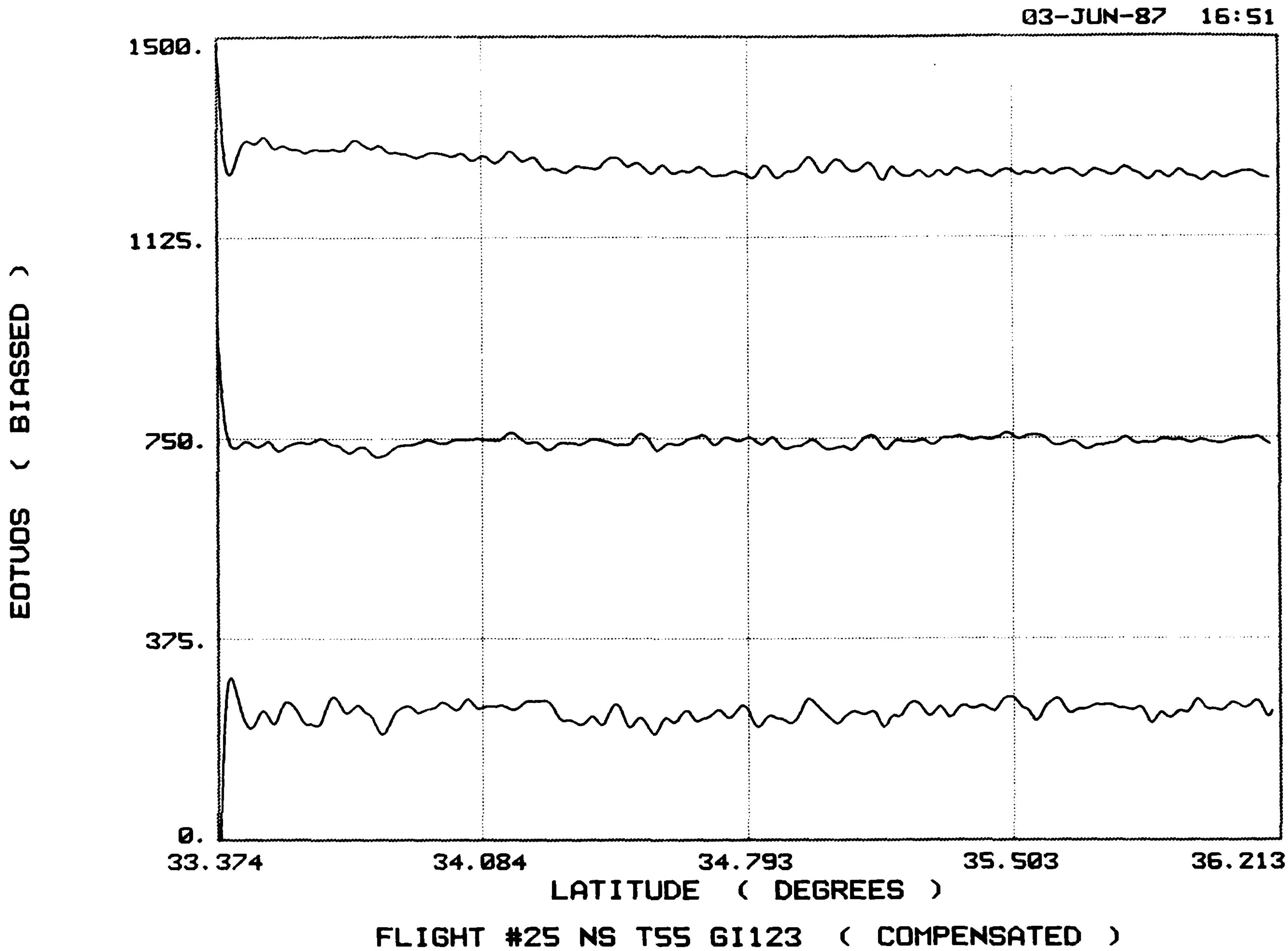
03-JUN-87 16:24
1500.
1125.
750.
375.
0.
EOTVOS (BIASSED)
33.375
34.085
34.794
35.504
36.214
LATITUDE (DEGREES)
FLIGHT #25 NS T53 GI123 (COMPENSATED)

FIGURE 26



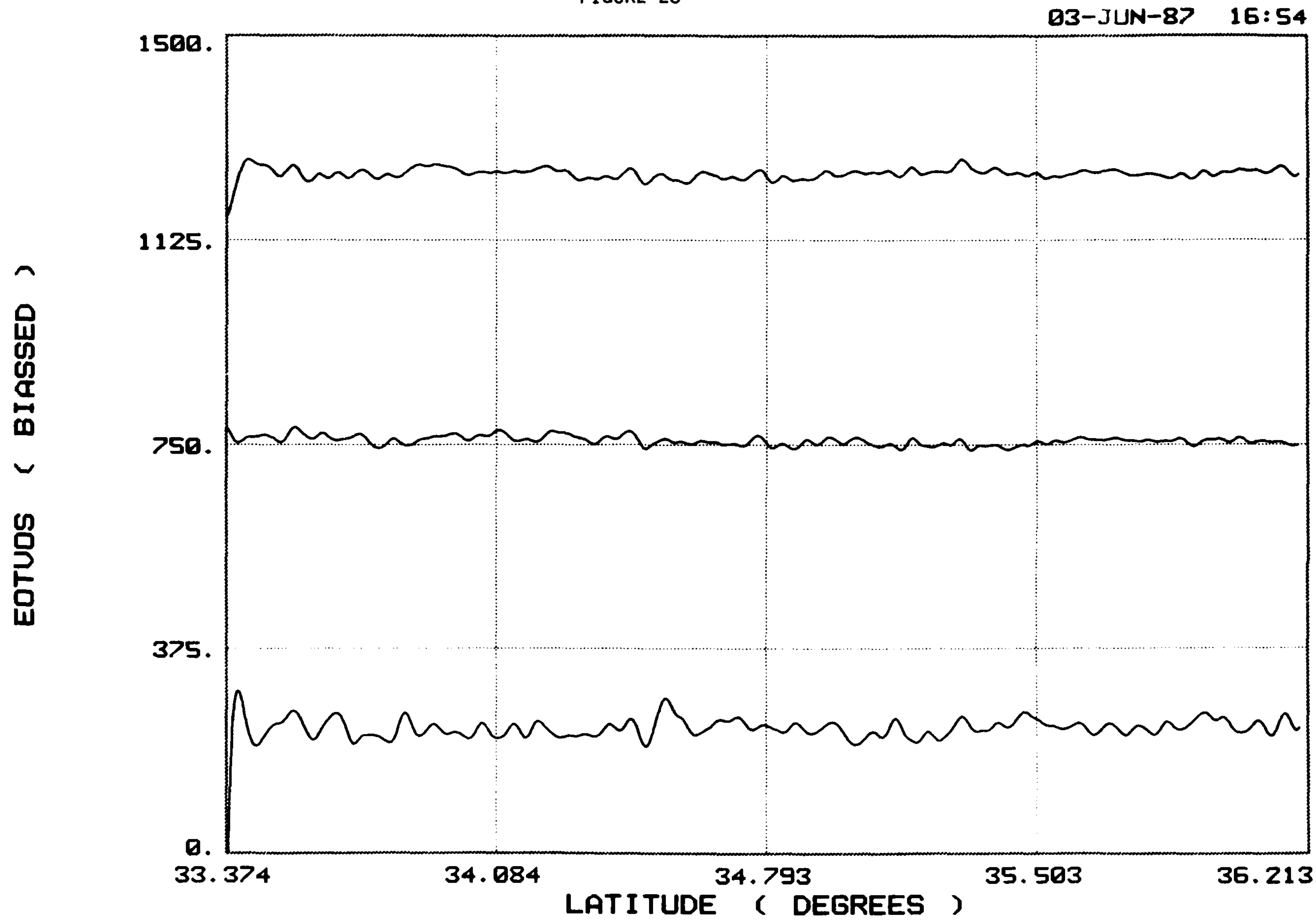
03-JUN-87 16:47
1500.
1125.
750.
375.
0.
EOTVOS (BIASSED)
33.375
34.035
34.794
35.504
36.214
LATITUDE (DEGREES)
FLIGHT #25 NS T53 GC123 (COMPENSATED)

FIGURE 27



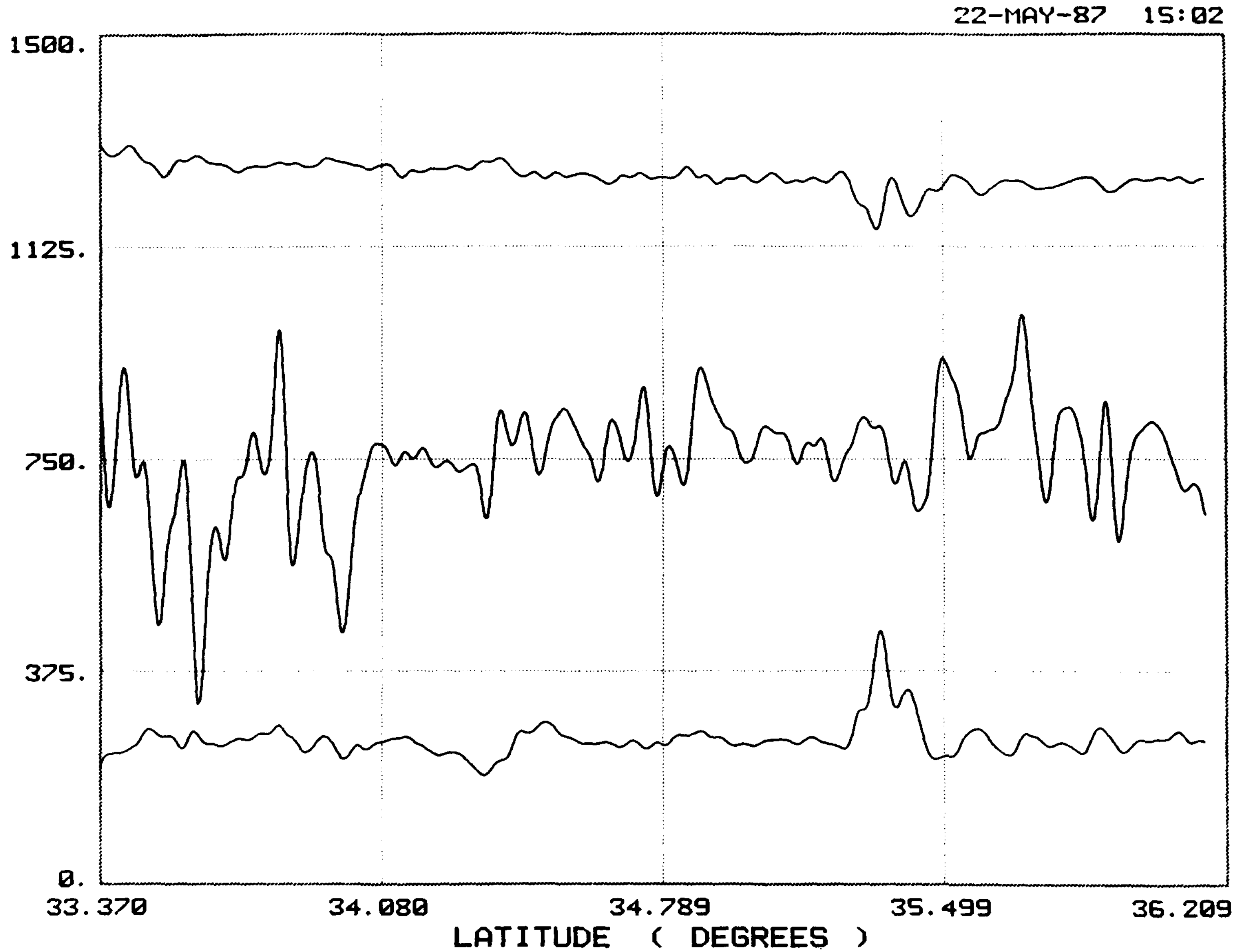
03-JUN-87 16:51
1500.
1125.
750.
375.
0.
33.374
34.084
34.793
35.503
36.213
LATITUDE (DEGREES)
EOTVOS (BIASSED)
FLIGHT #25 NS T55 GI123 (COMPENSATED)

FIGURE 28



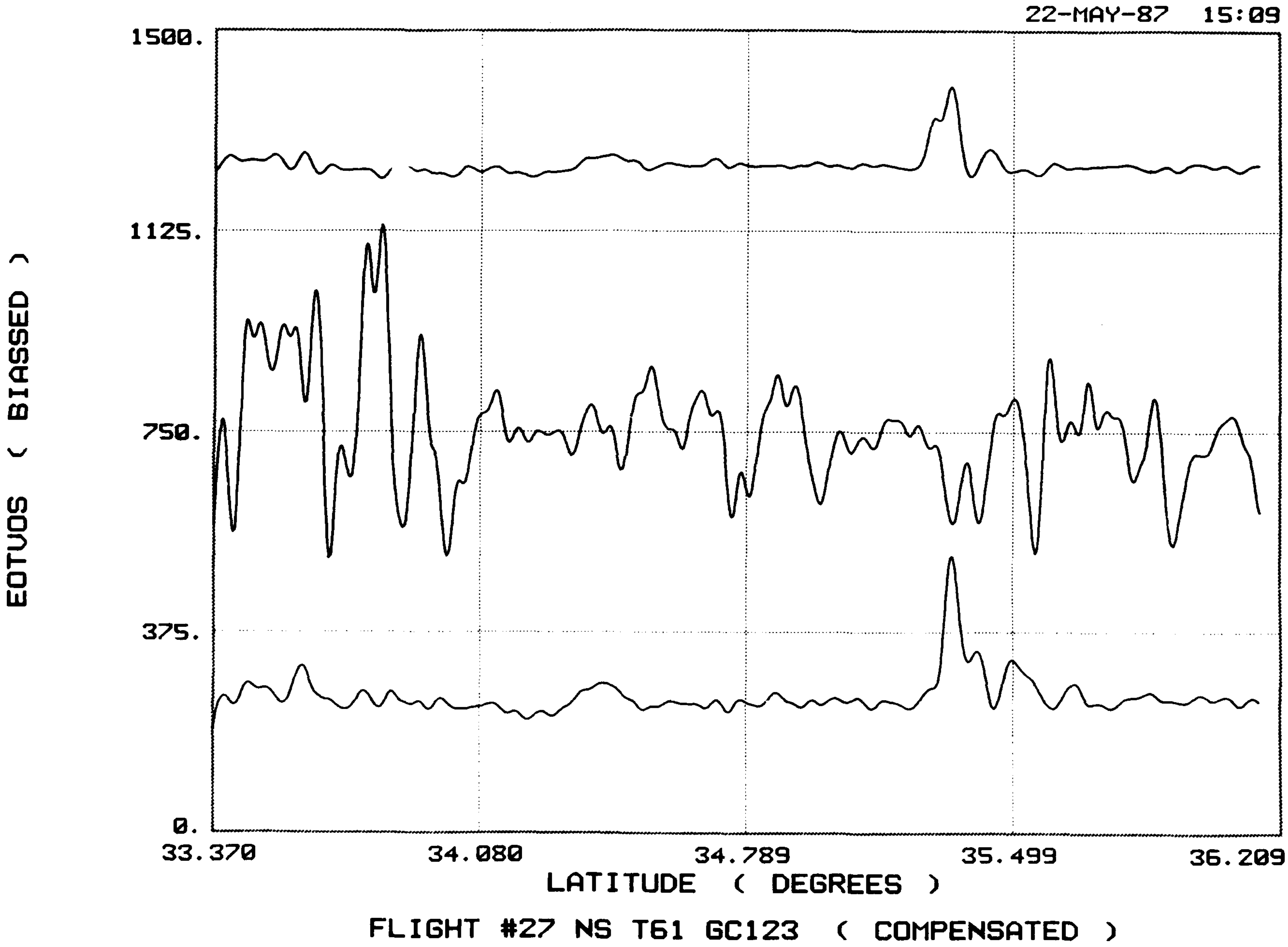
FLIGHT #25 NS T55 GC123 (COMPENSATED)

FIGURE 29



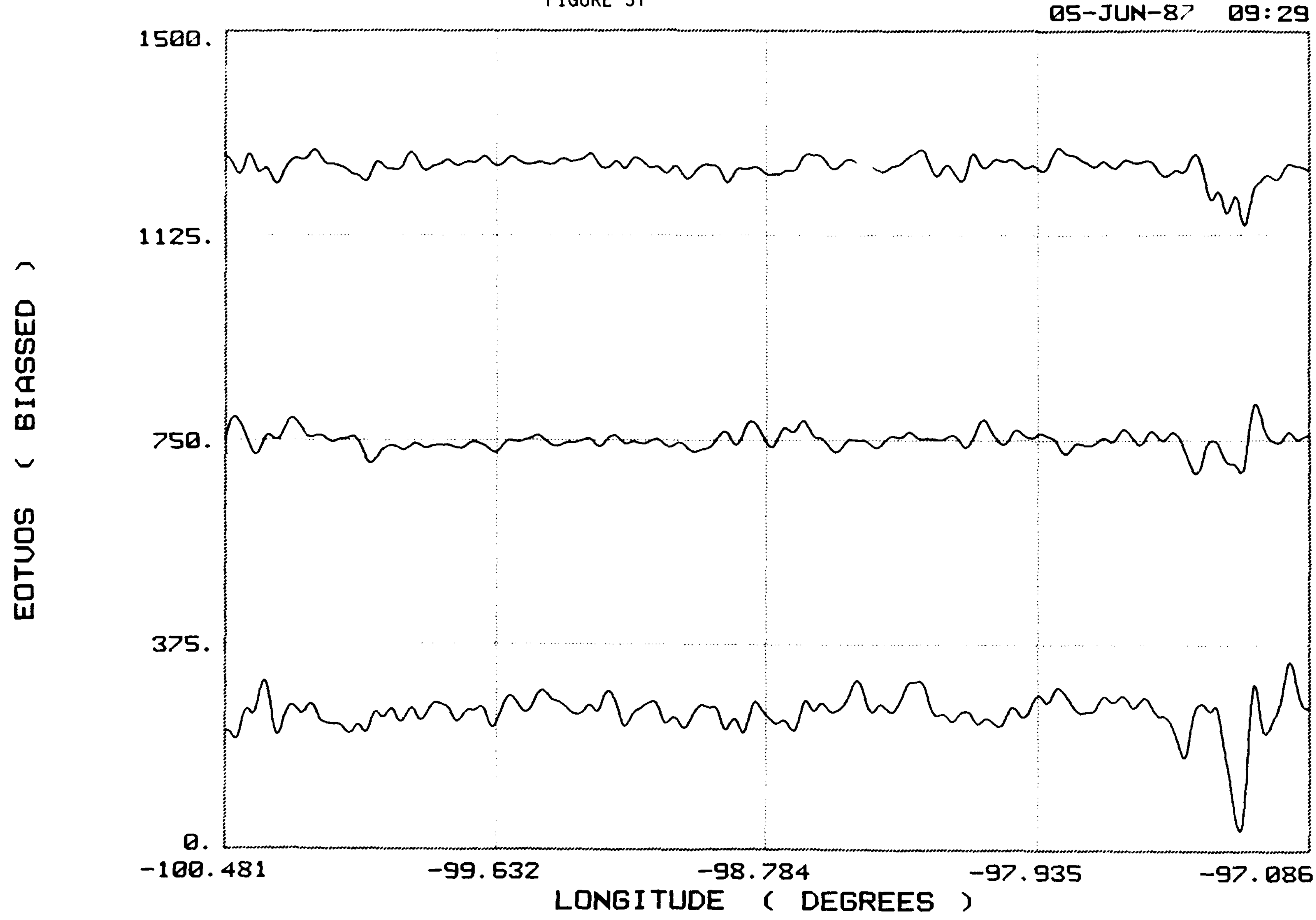
FLIGHT #27 NS T61 GI123 (COMPENSATED)

FIGURE 30



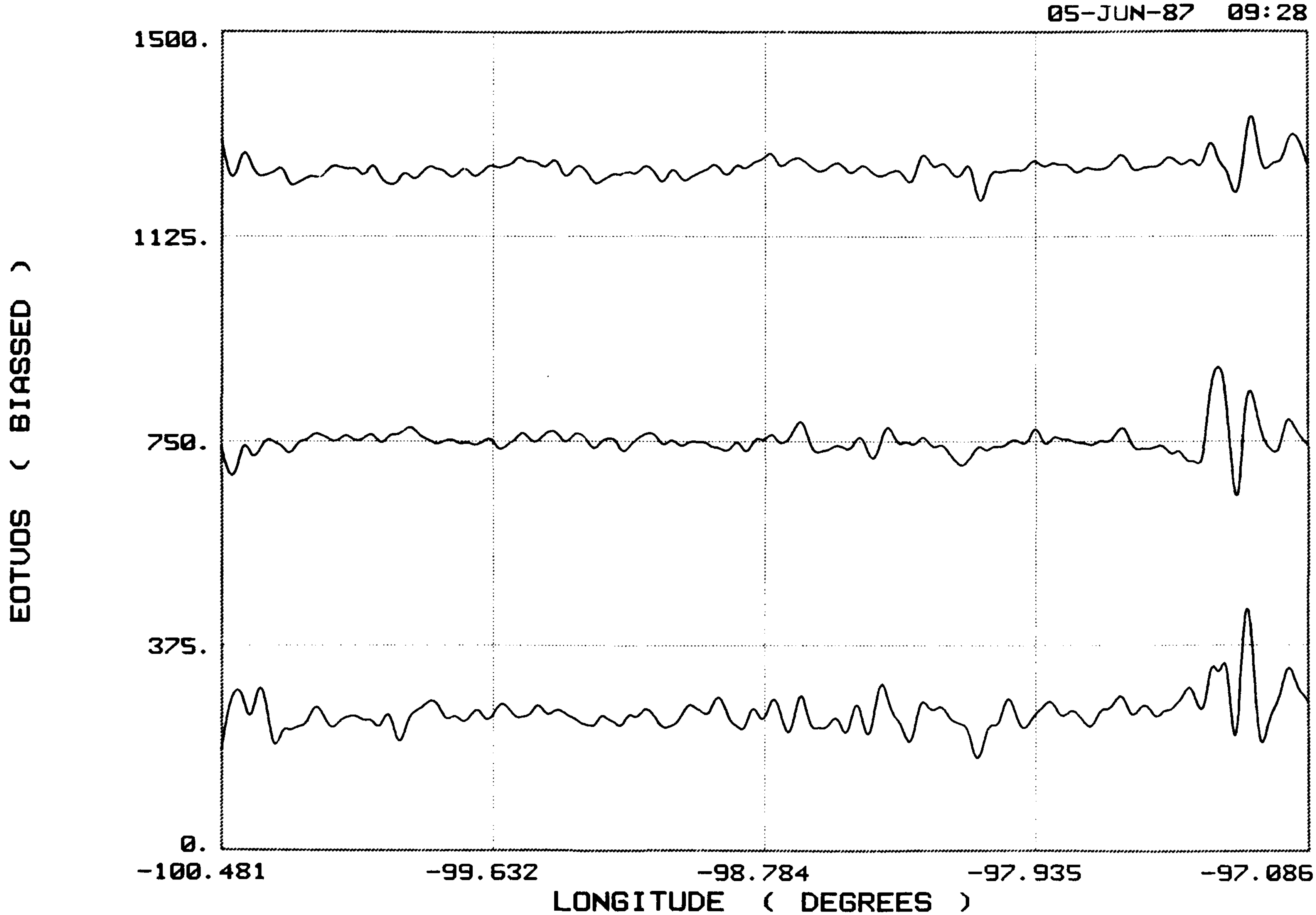
22-MAY-87 15:09
1500.
1125.
750.
375.
0.
EOTVOS (BIASSED)
33.370
34.080
34.789
35.499
36.209
LATITUDE (DEGREES)
FLIGHT #27 NS T61 GC123 (COMPENSATED)

FIGURE 31



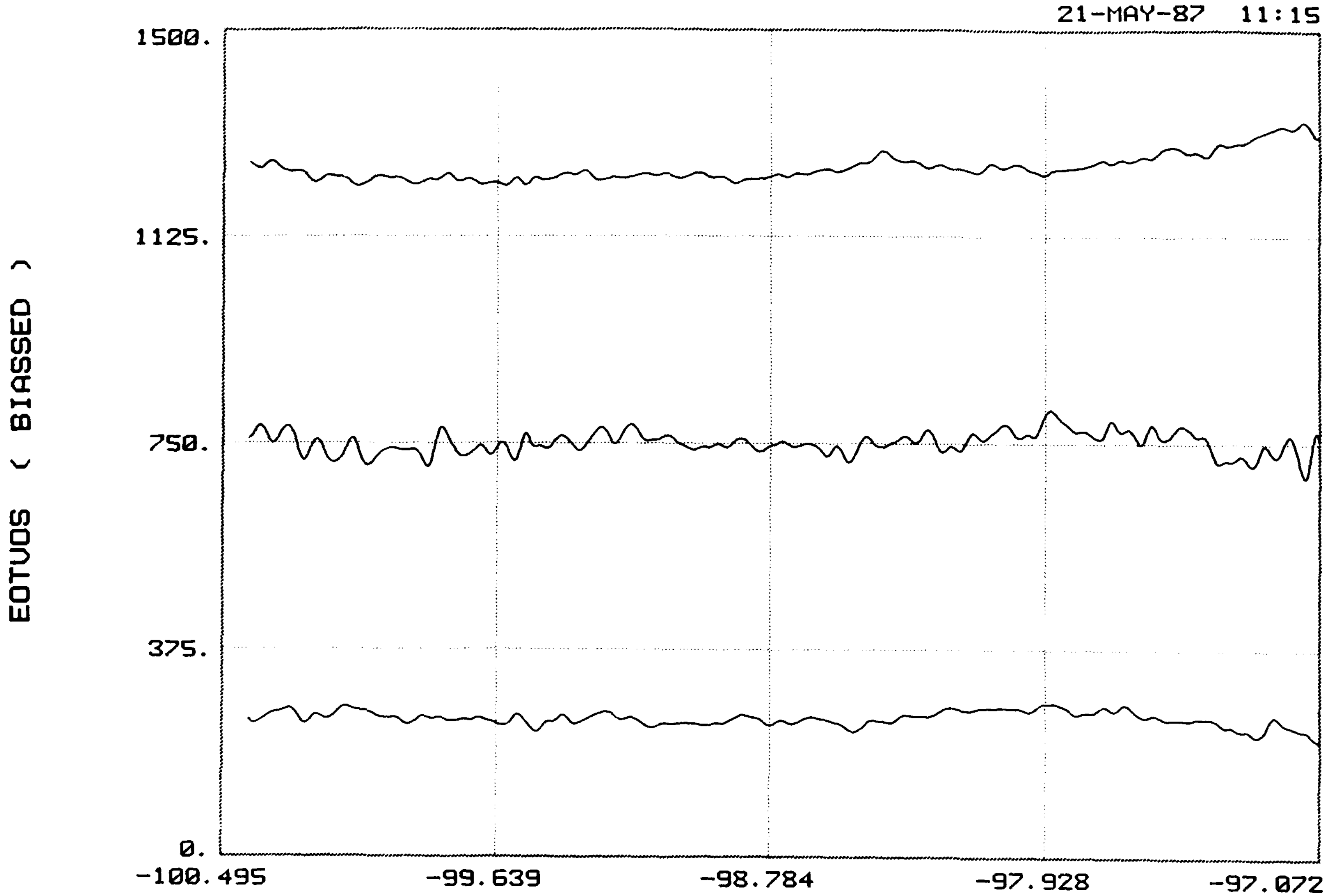
FLIGHT #19 EW T7 GI123 (COMPENSATED)

FIGURE 32



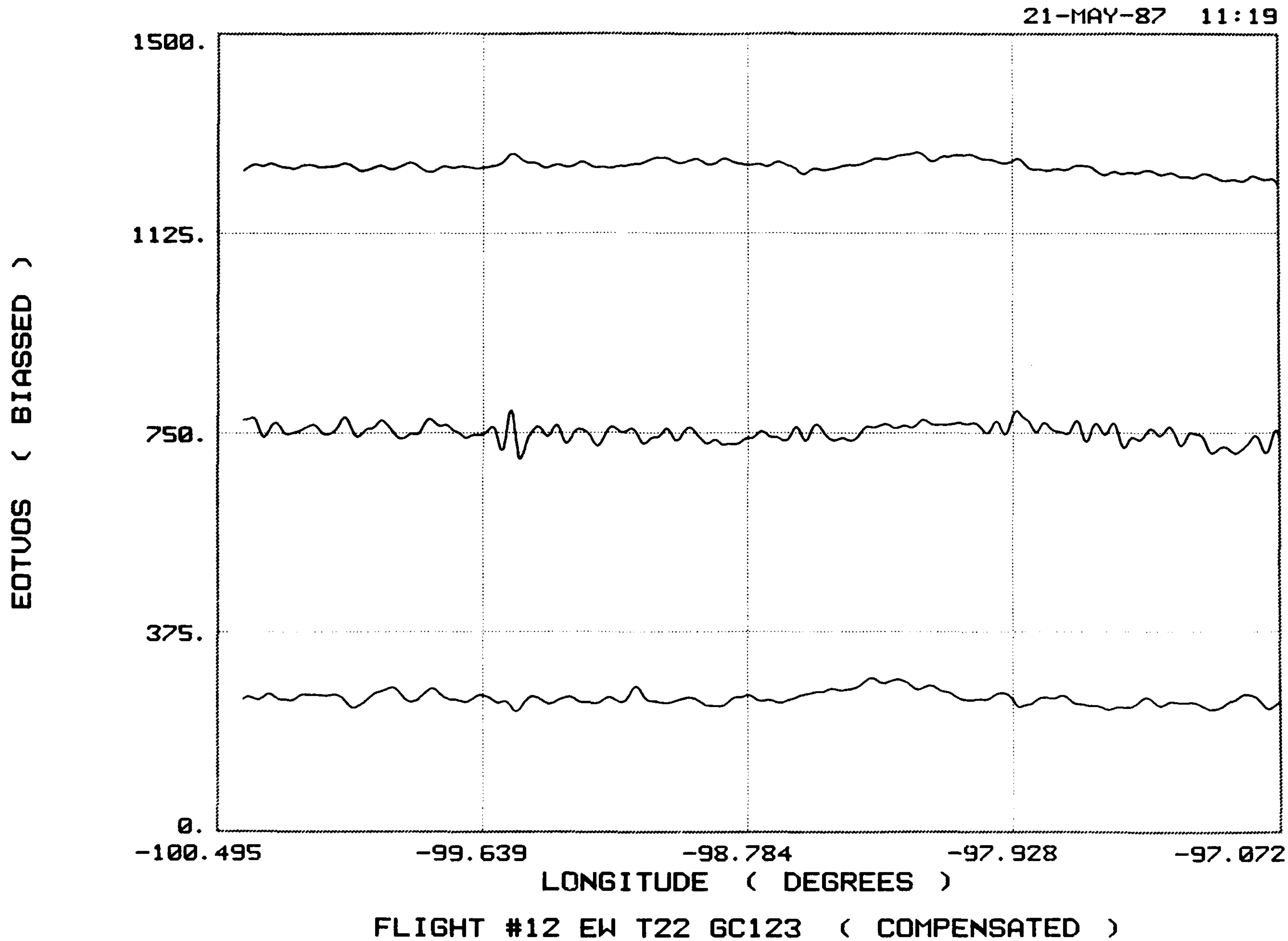
FLIGHT #19 EW T7 GC123 (COMPENSATED)

FIGURE 33



FLIGHT #12 EW T22 GI123 (COMPENSATED)

FIGURE 34



21-MAY-87 11:19
1500.
1125.
750.
375.
0.
EOTVOS (BIASSED)
-100.495
-99.639
-98.784
-97.928
-97.072
LONGITUDE (DEGREES)
FLIGHT #12 EW T22 GC123 (COMPENSATED)

FIGURE 35

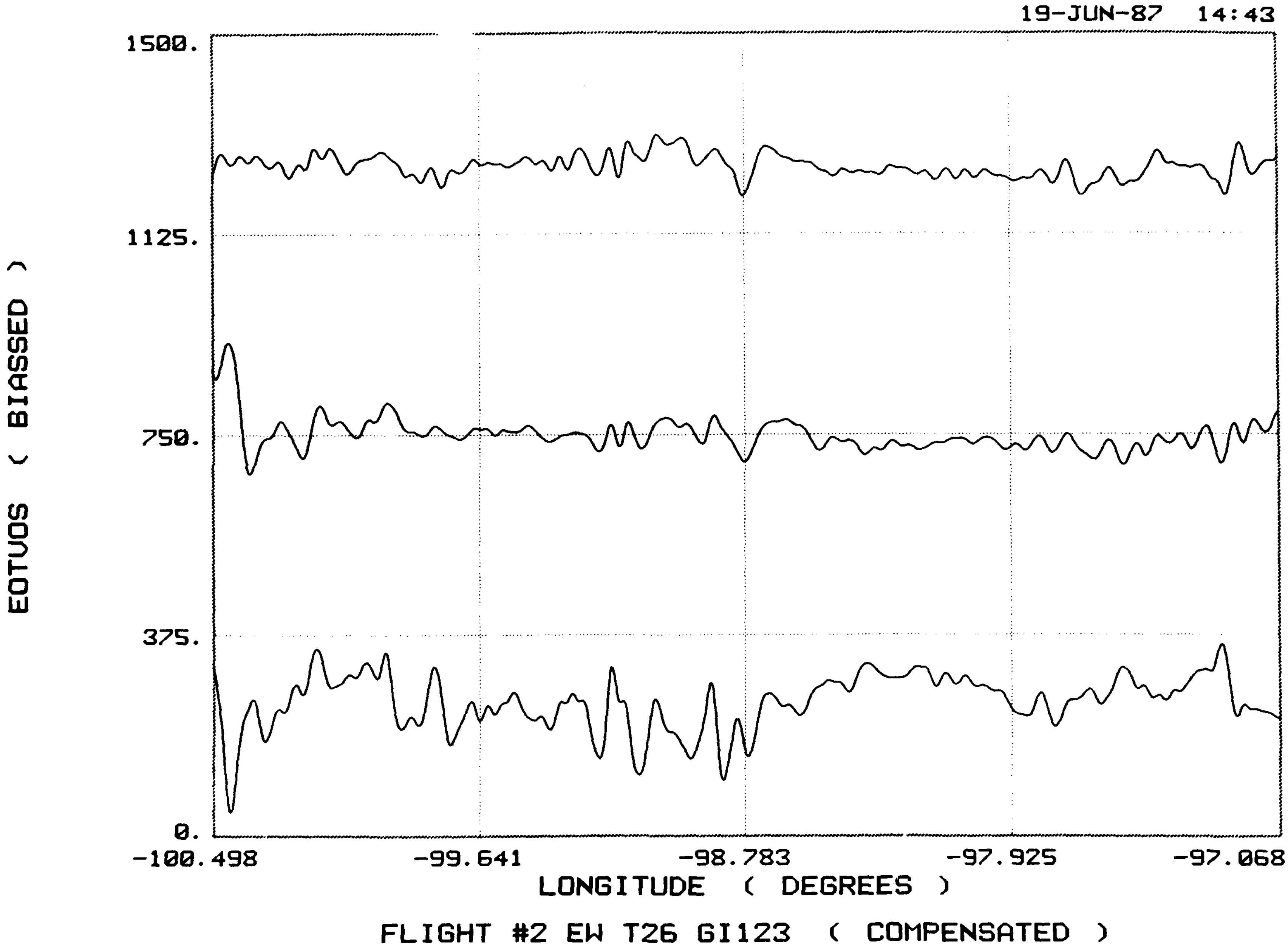

19-JUN-87 14:43
1500.
1125.
750.
375.
0.
EOTUOS (BIASSED)
-100.498
-99.641
-98.783
-97.925
-97.068
LONGITUDE (DEGREES)
FLIGHT #2 EW T26 GI123 (COMPENSATED)

FIGURE 36

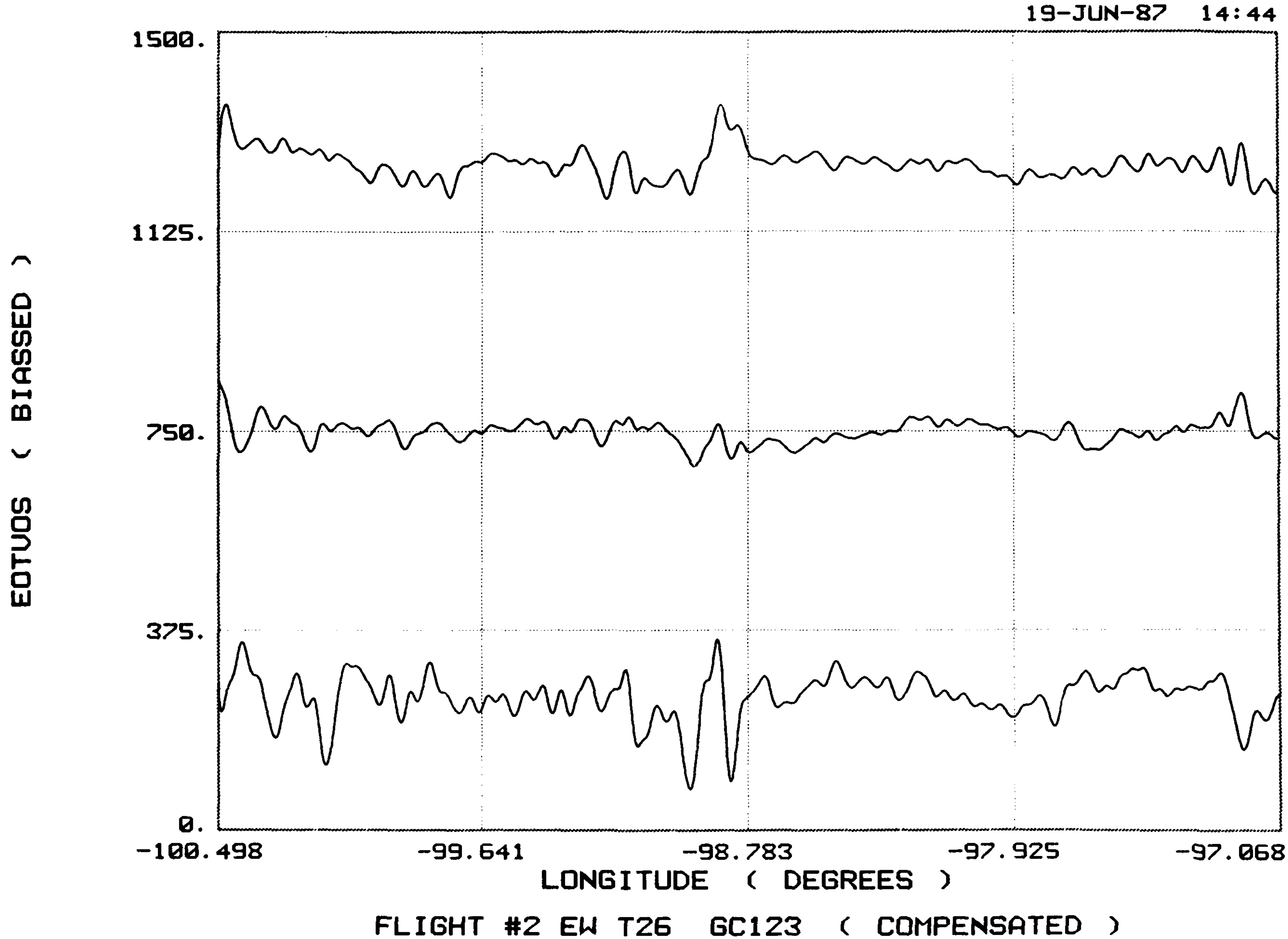
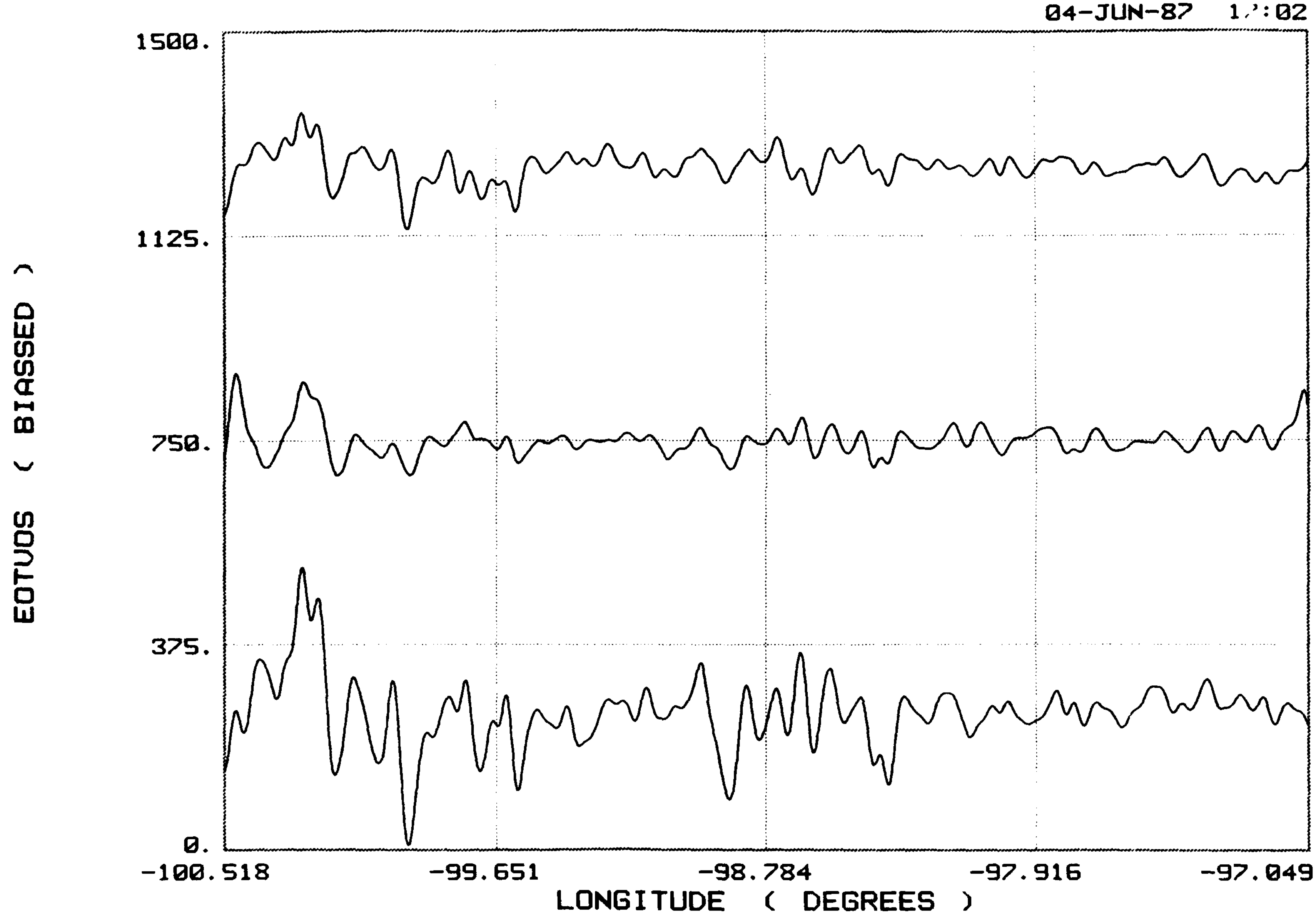
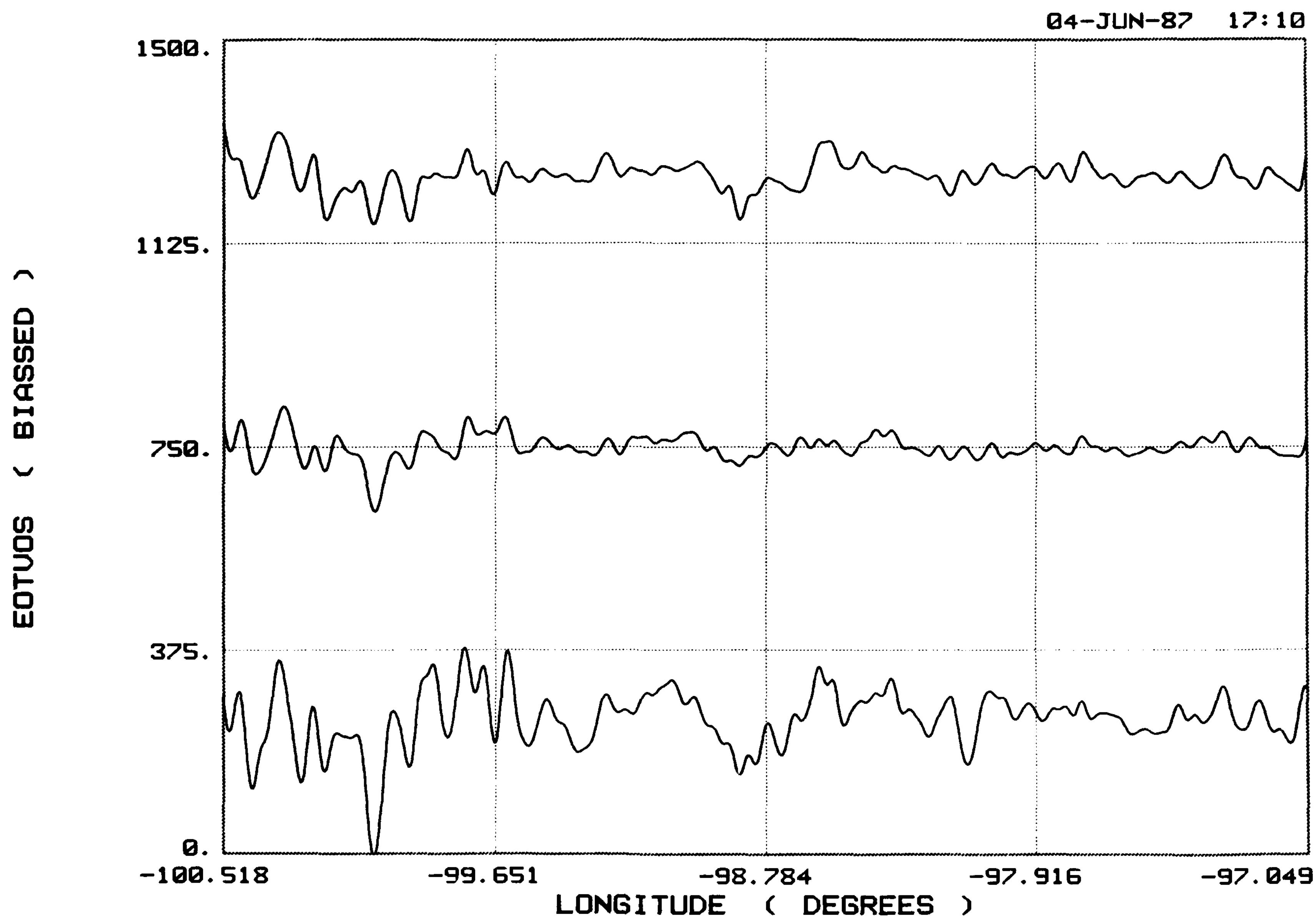

19-JUN-87 14:44
1500.
1125.
750.
375.
0.
EOTVOS (BIASSED)
-100.498
-99.641
-98.783
-97.925
-97.068
LONGITUDE (DEGREES)
FLIGHT #2 EW T26 GC123 (COMPENSATED)

FIGURE 37



FLIGHT #29 EW T47 GI123 (COMPENSATED)

FIGURE 38



FLIGHT #29 EW T47 GC123 (COMPENSATED)

FIGURE 39

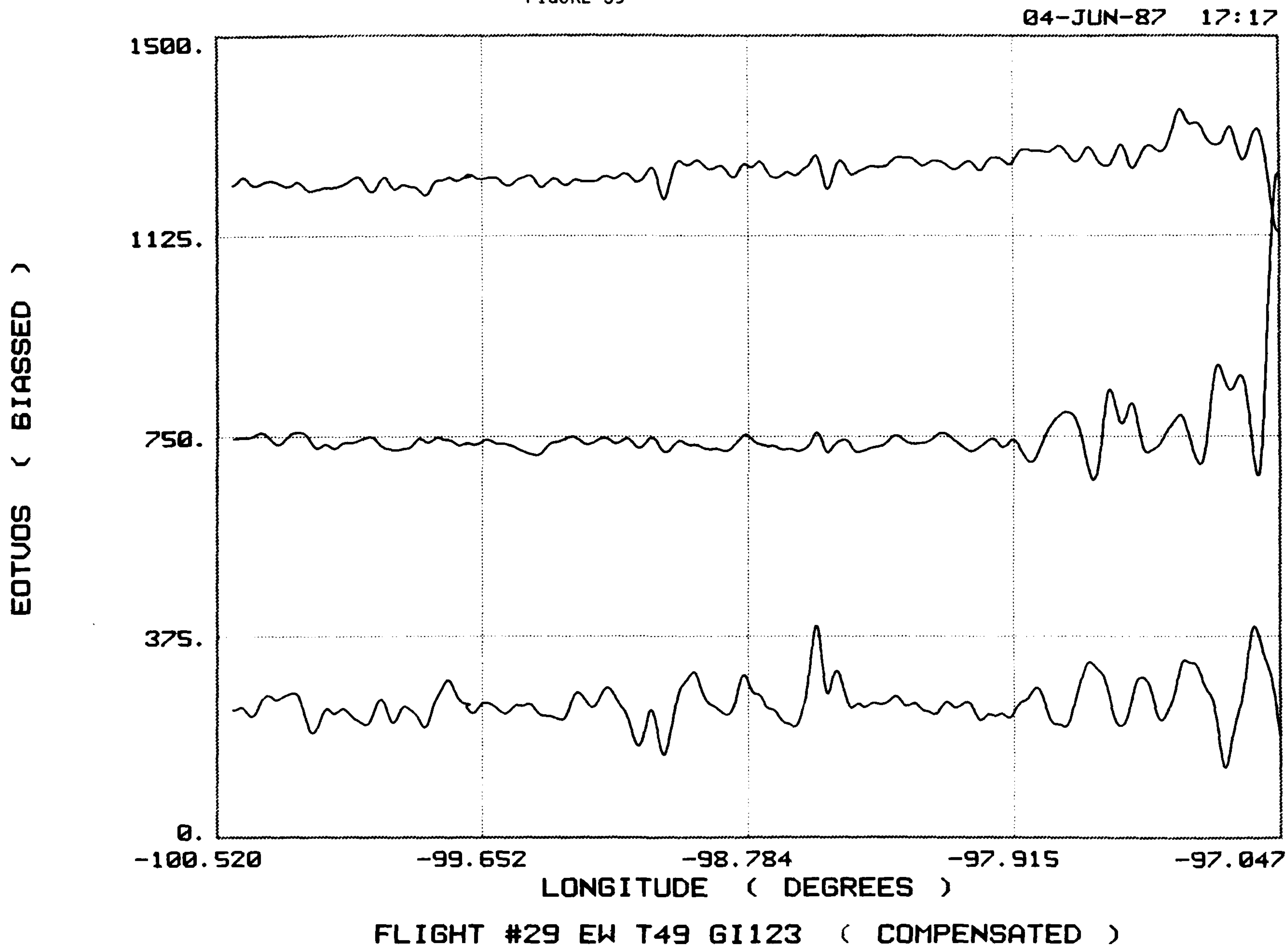
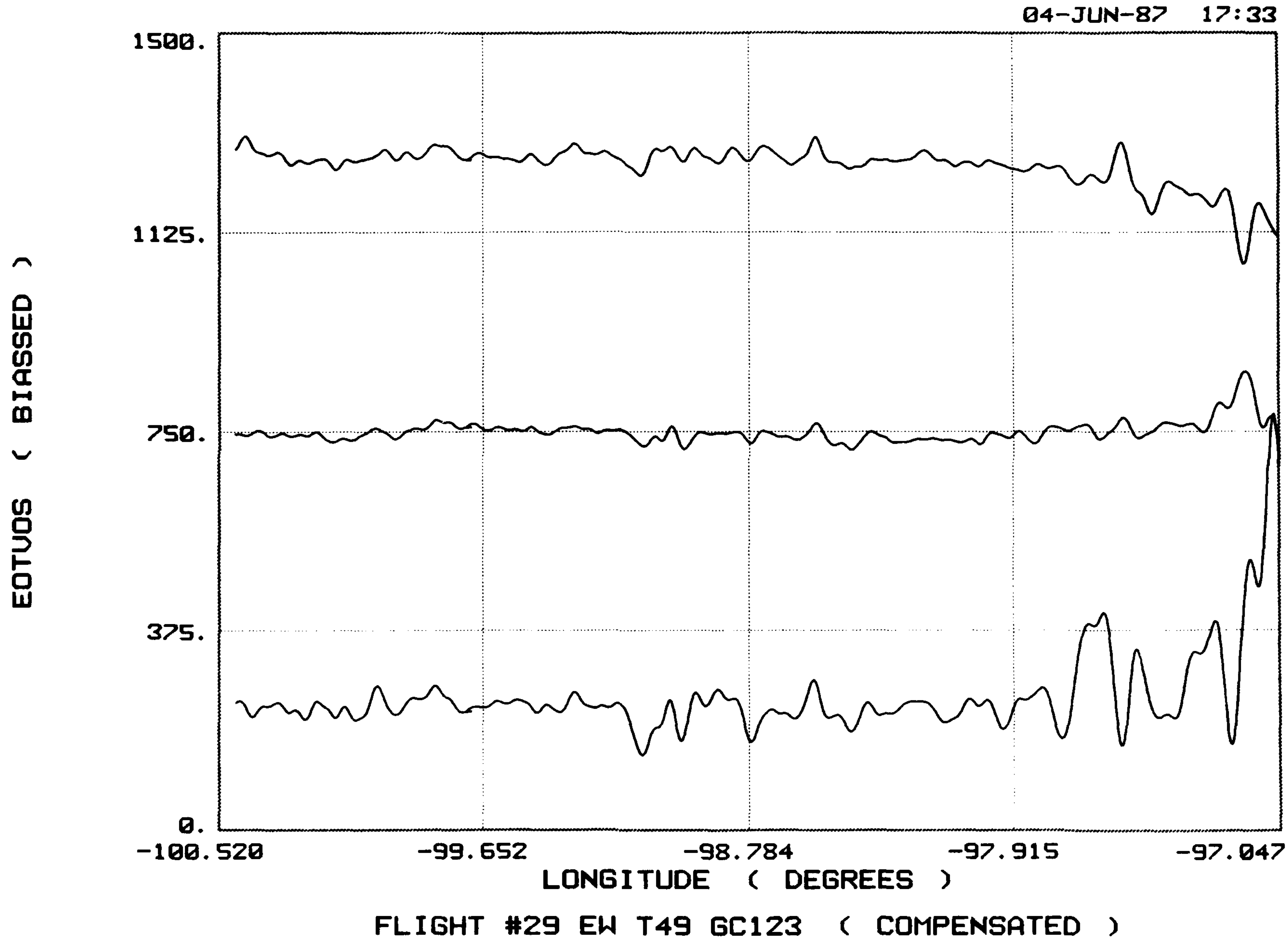
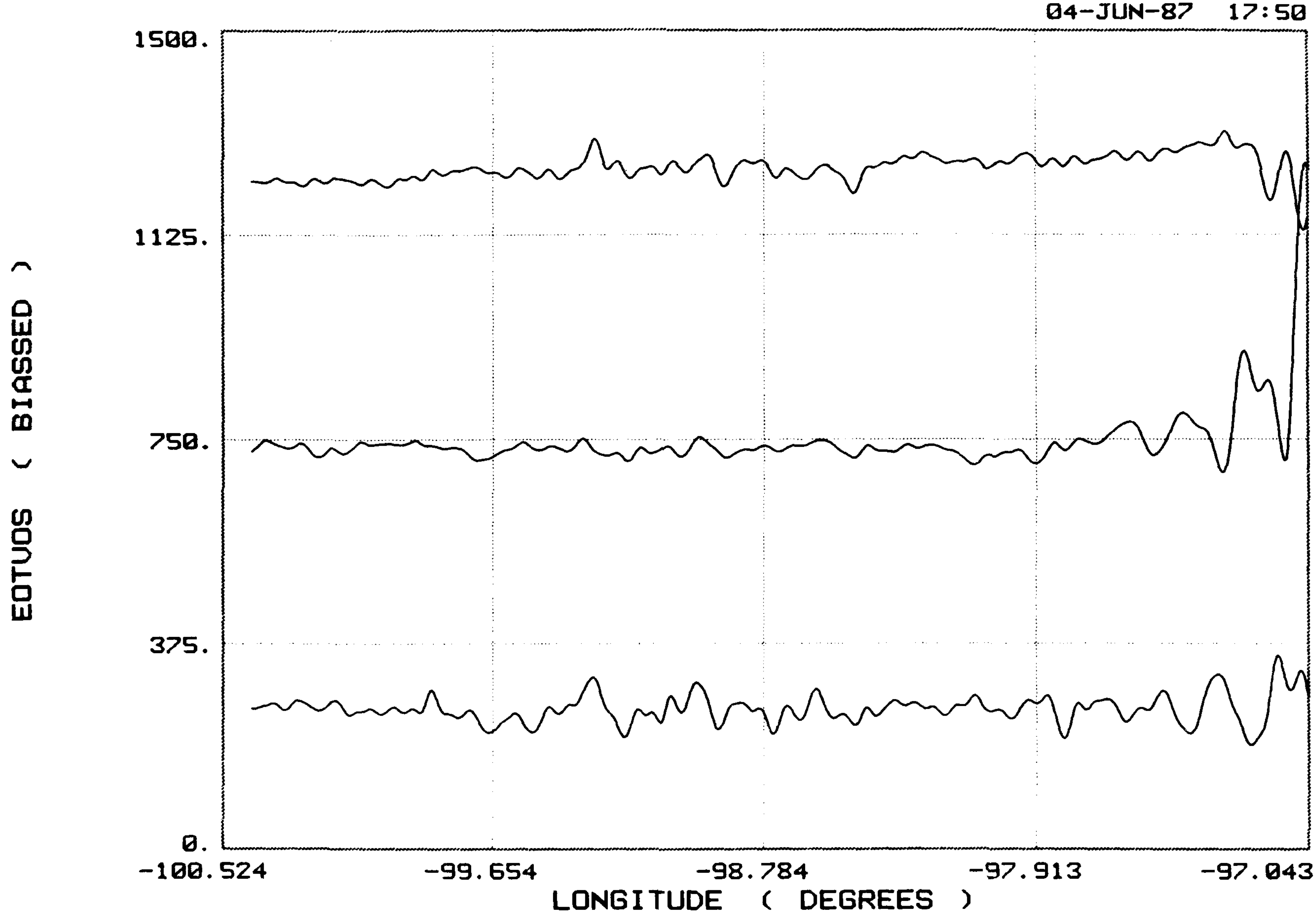

04-JUN-87 17:17
1500.
1125.
750.
375.
0.
EOTVOS (BIASSED)
-100.520
-99.652
-98.784
-97.915
-97.047
LONGITUDE (DEGREES)
FLIGHT #29 EW T49 GI123 (COMPENSATED)

FIGURE 40



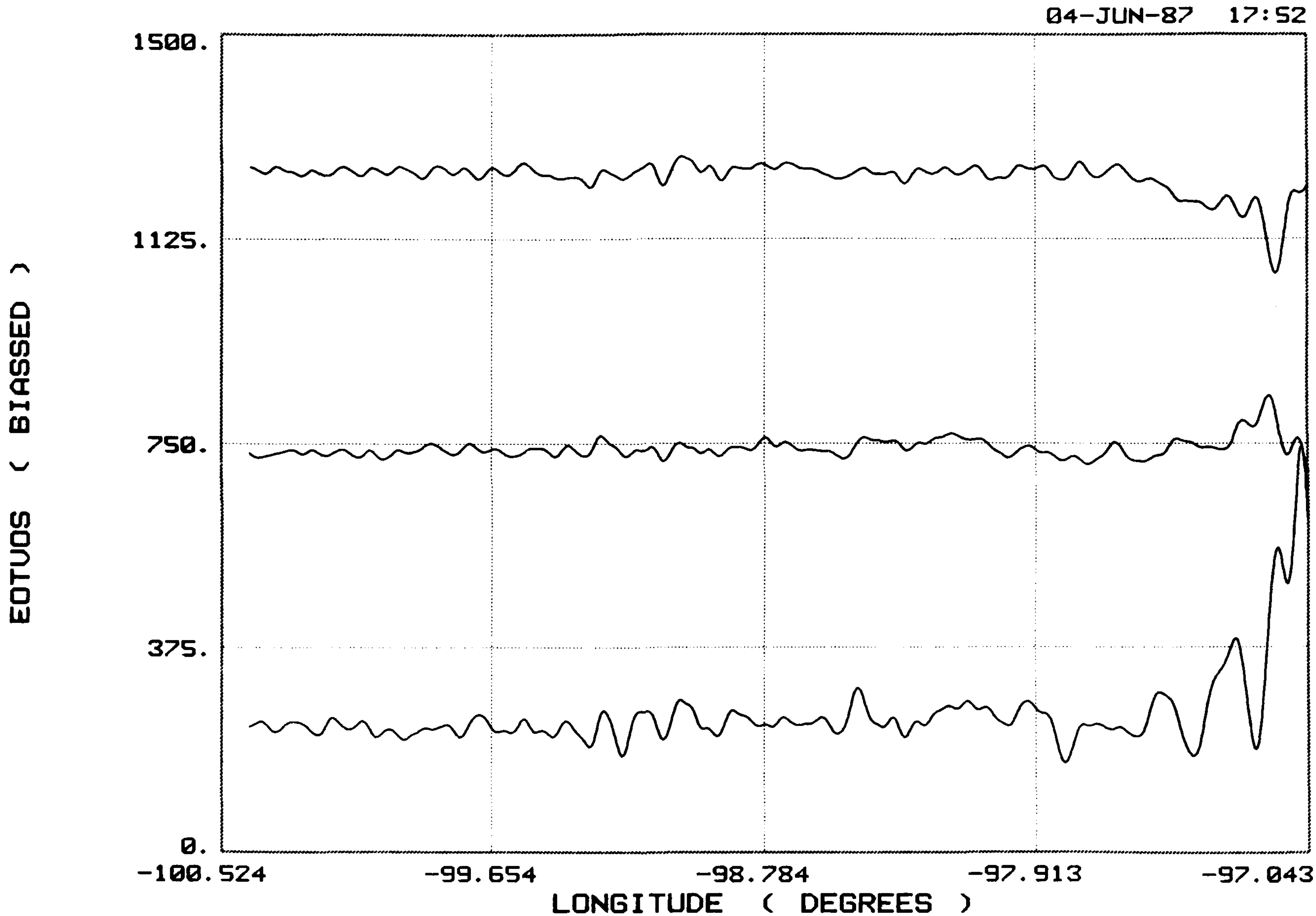
04-JUN-87 17:33
1500.
1125.
750.
375.
0.
EOTVOS (BIASSED)
-100.520
-99.652
-98.784
-97.915
-97.047
LONGITUDE (DEGREES)
FLIGHT #29 EW T49 GC123 (COMPENSATED)

FIGURE 41



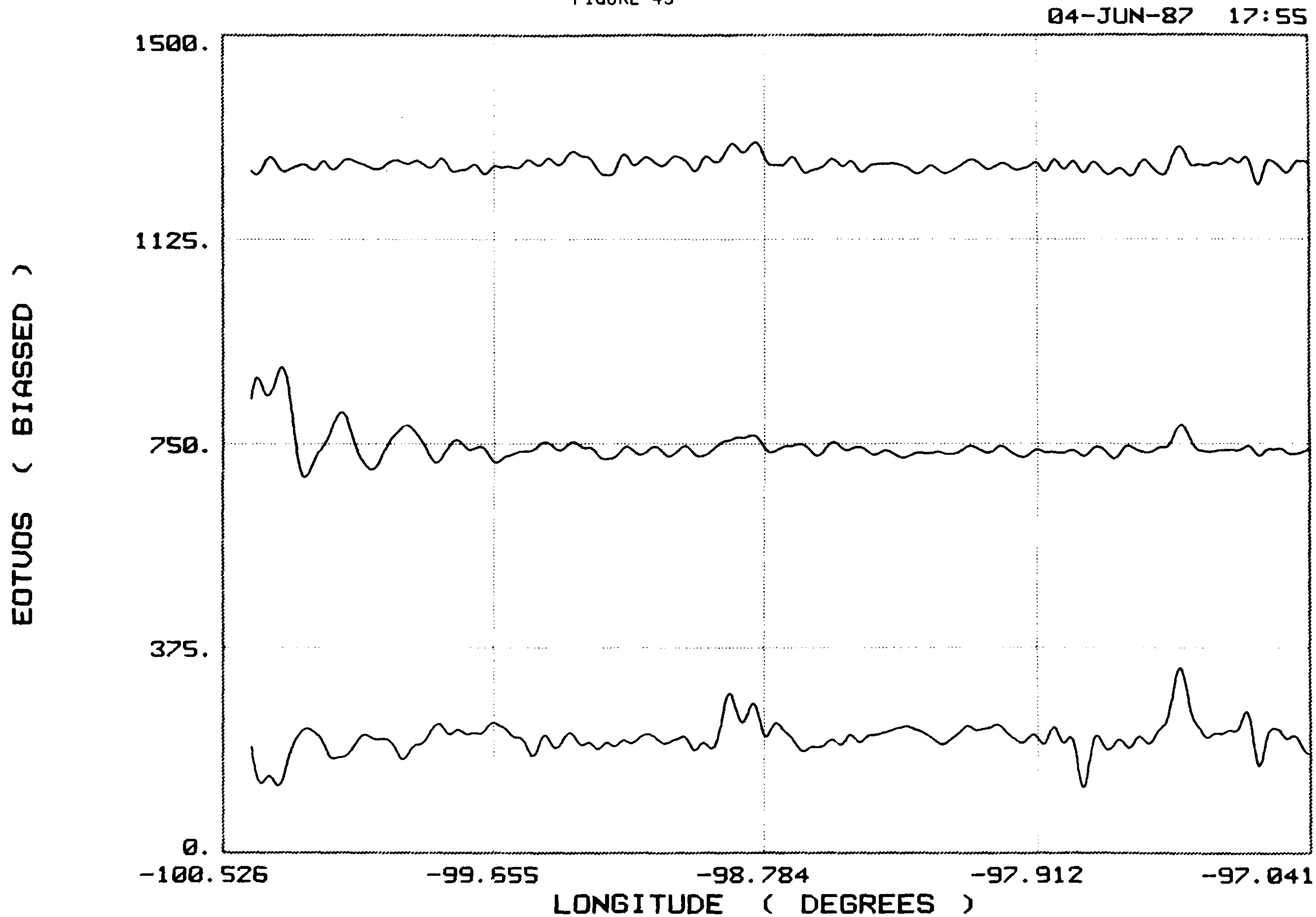
FLIGHT #29 EW T53 GI123 (COMPENSATED)

FIGURE 42



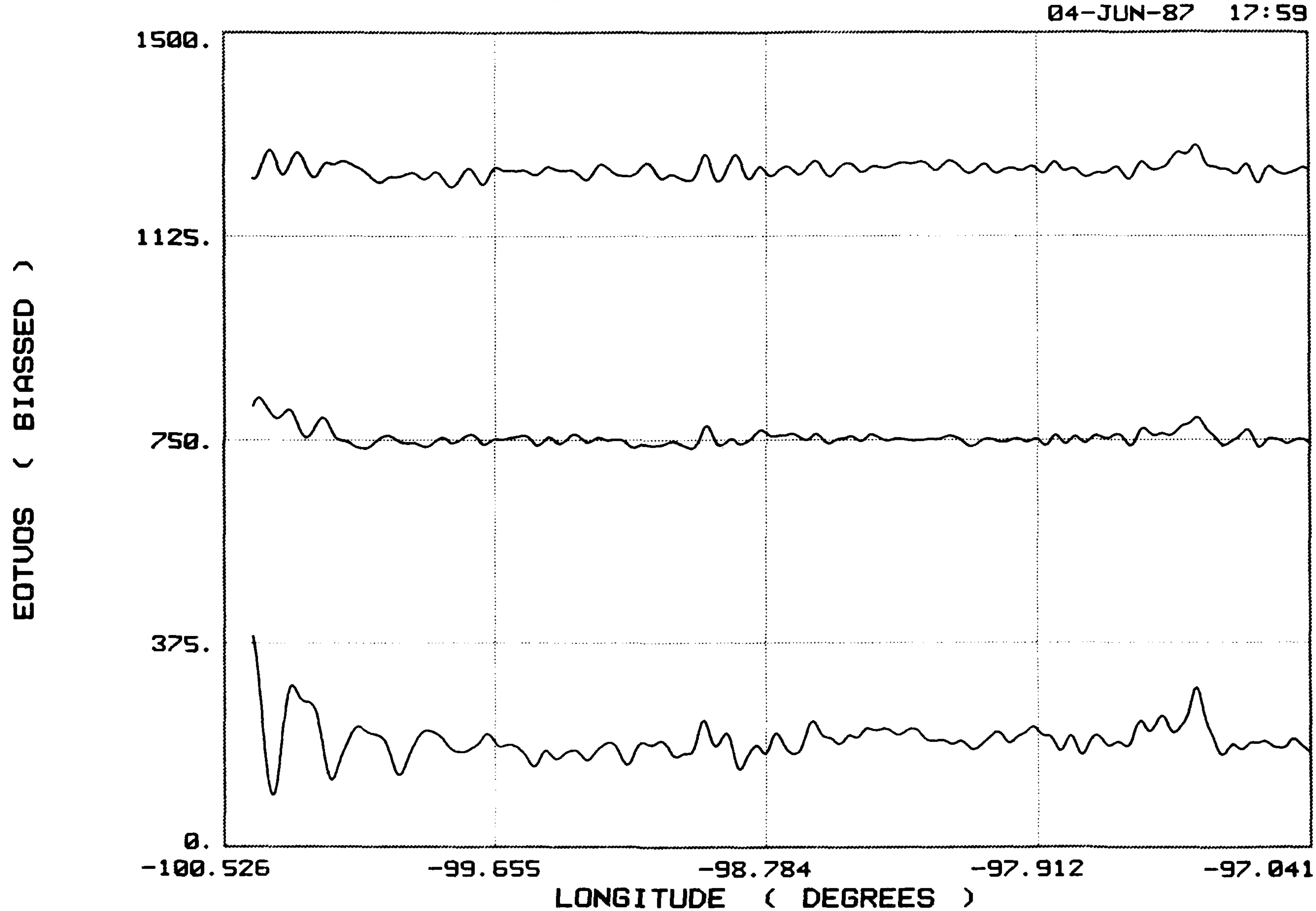
FLIGHT #29 EW T53 GC123 (COMPENSATED)

FIGURE 43



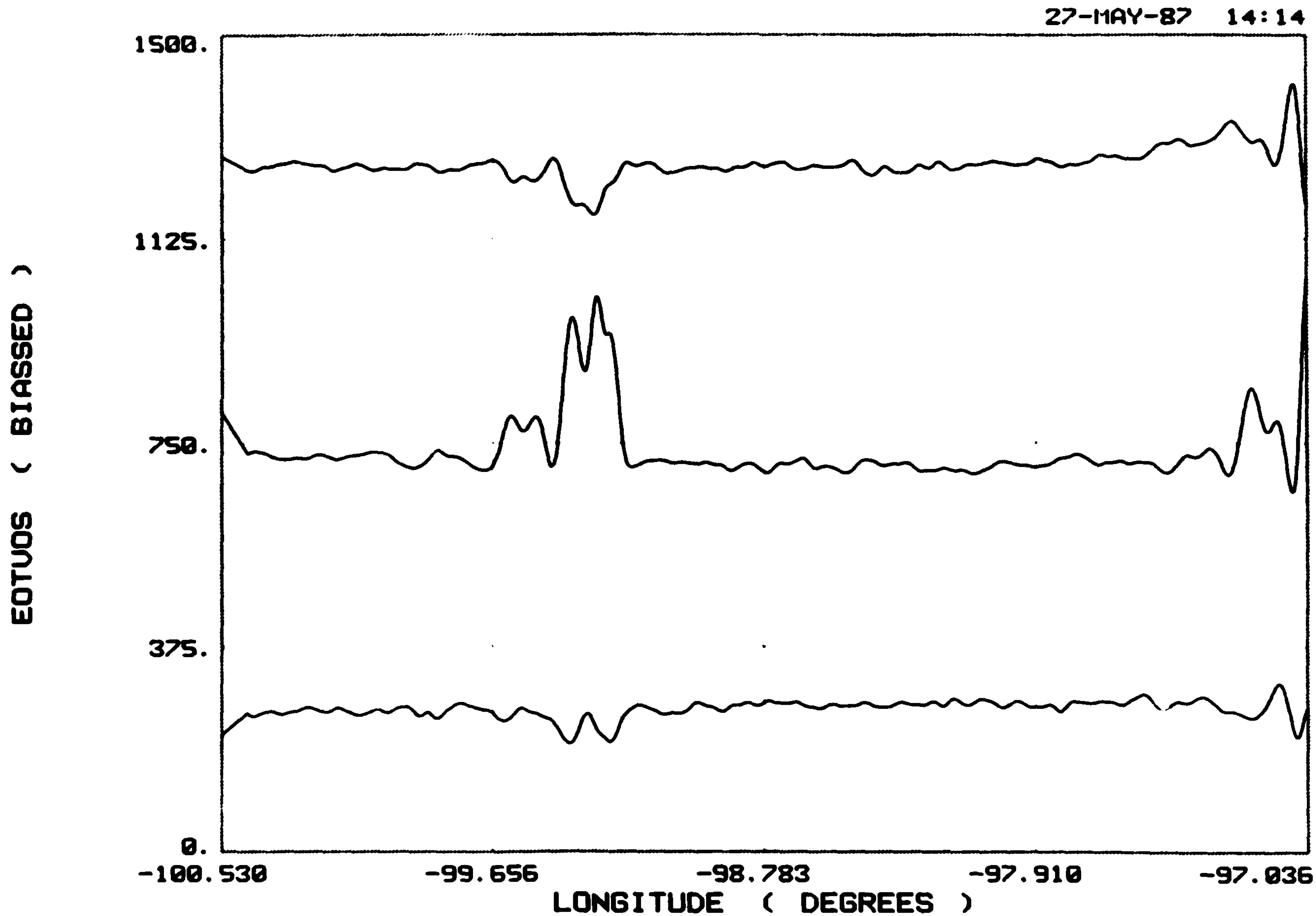
FLIGHT #29 EW TSS GI123 (COMPENSATED)

FIGURE 44



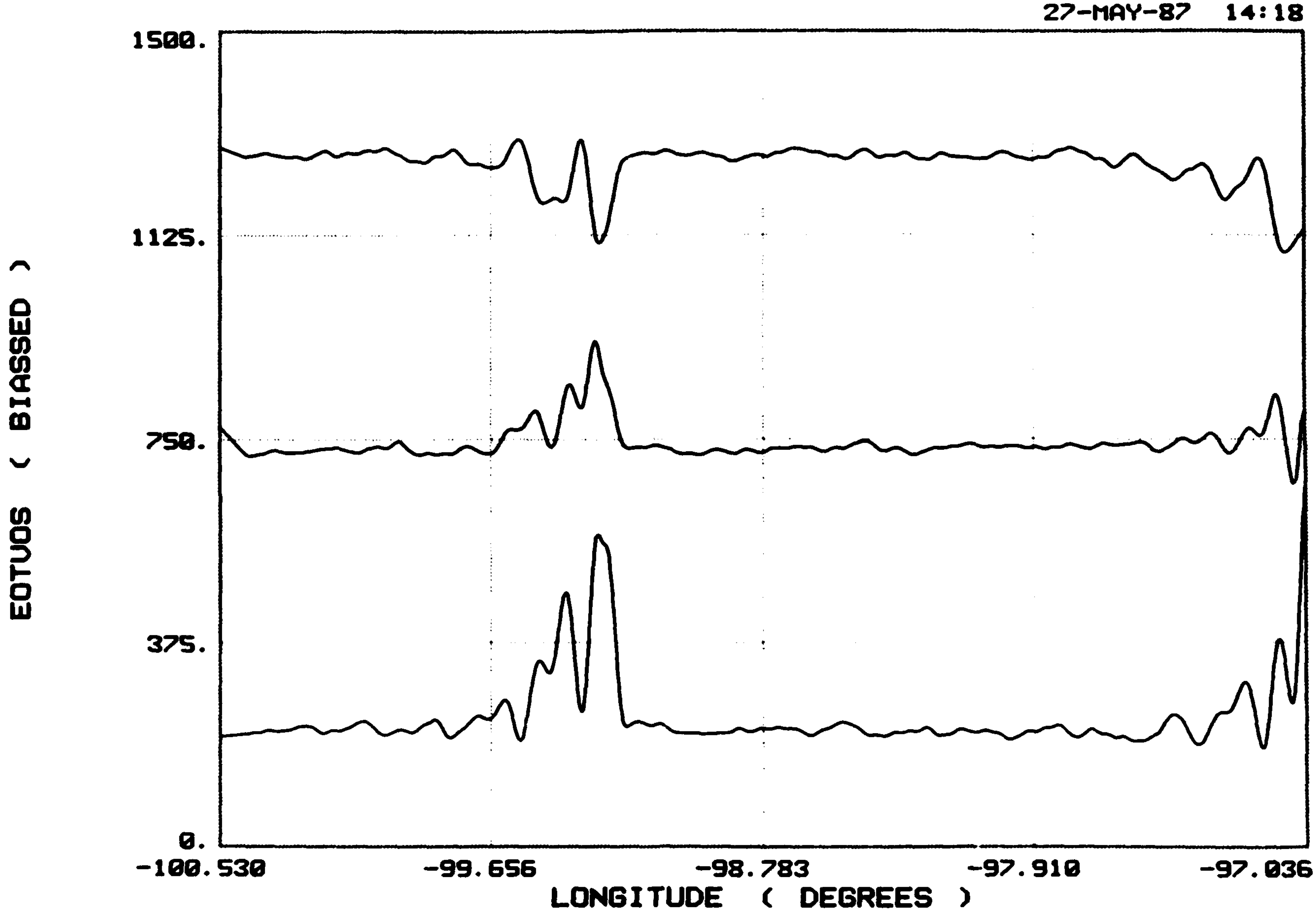
FLIGHT #29 EW T55 GC123 (COMPENSATED)

FIGURE 45



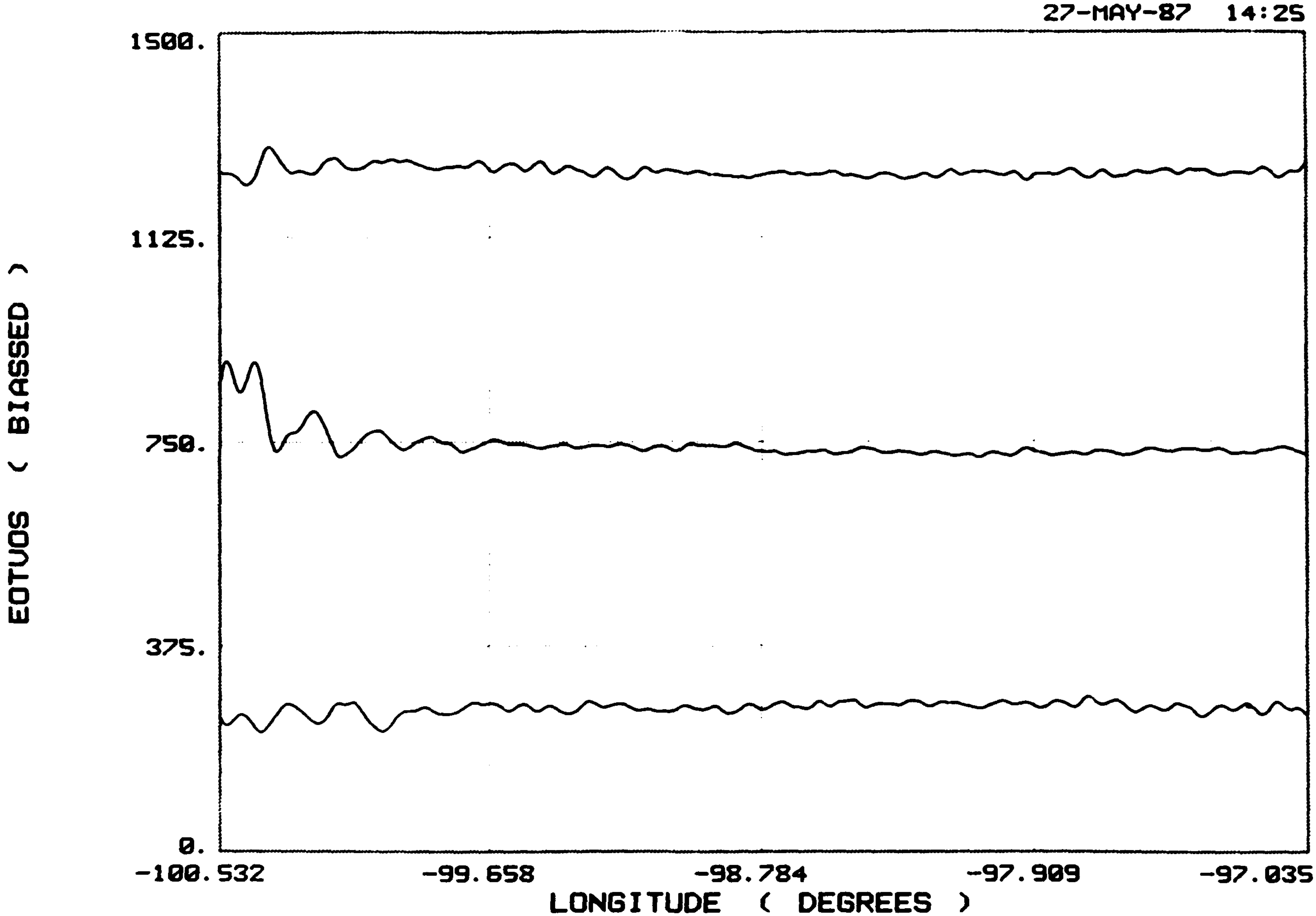
FLIGHT #30 EW T60 GI123 (COMPENSATED)

FIGURE 46



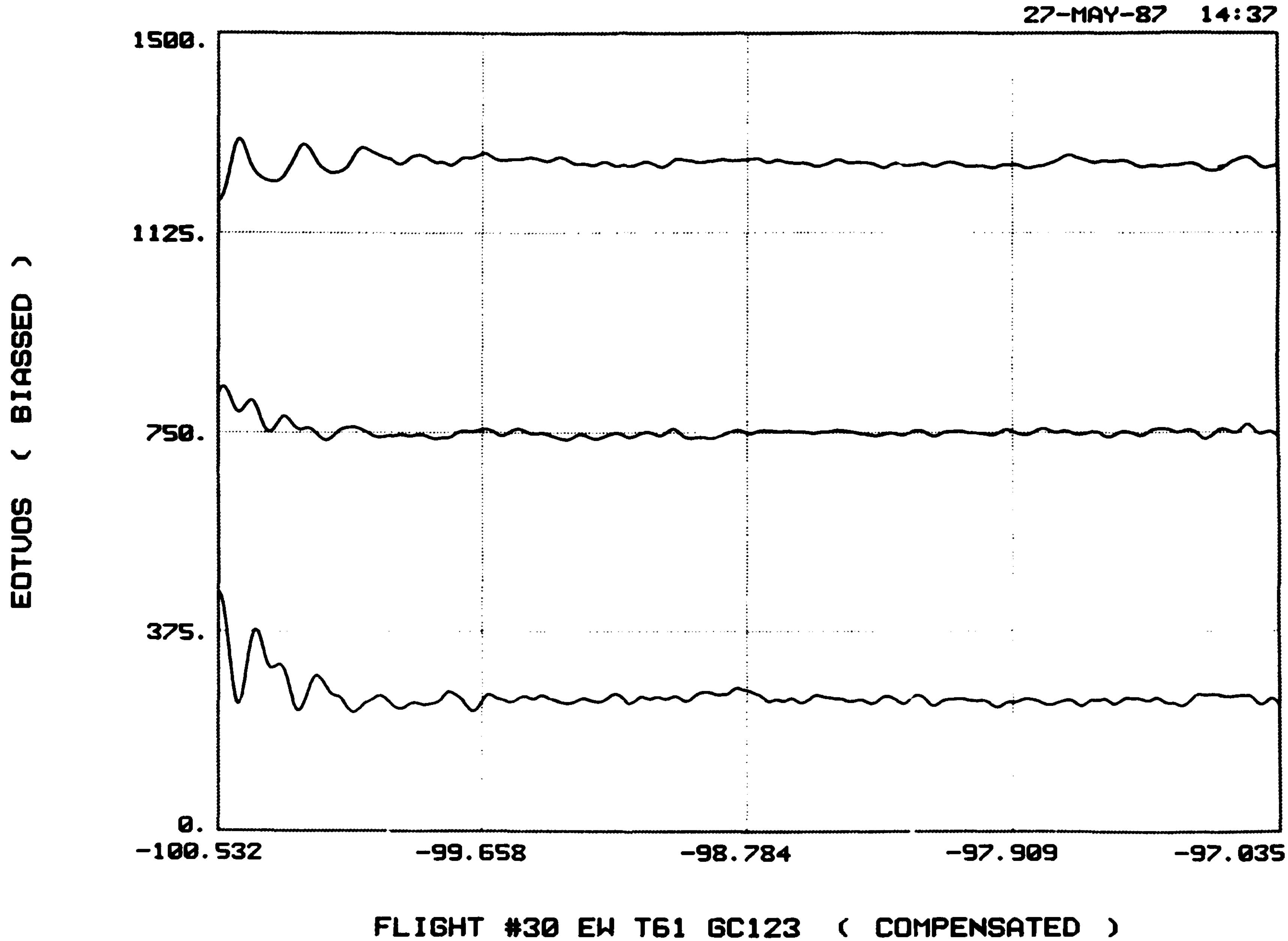
FLIGHT #30 EW T60 GC123 (COMPENSATED)

FIGURE 47

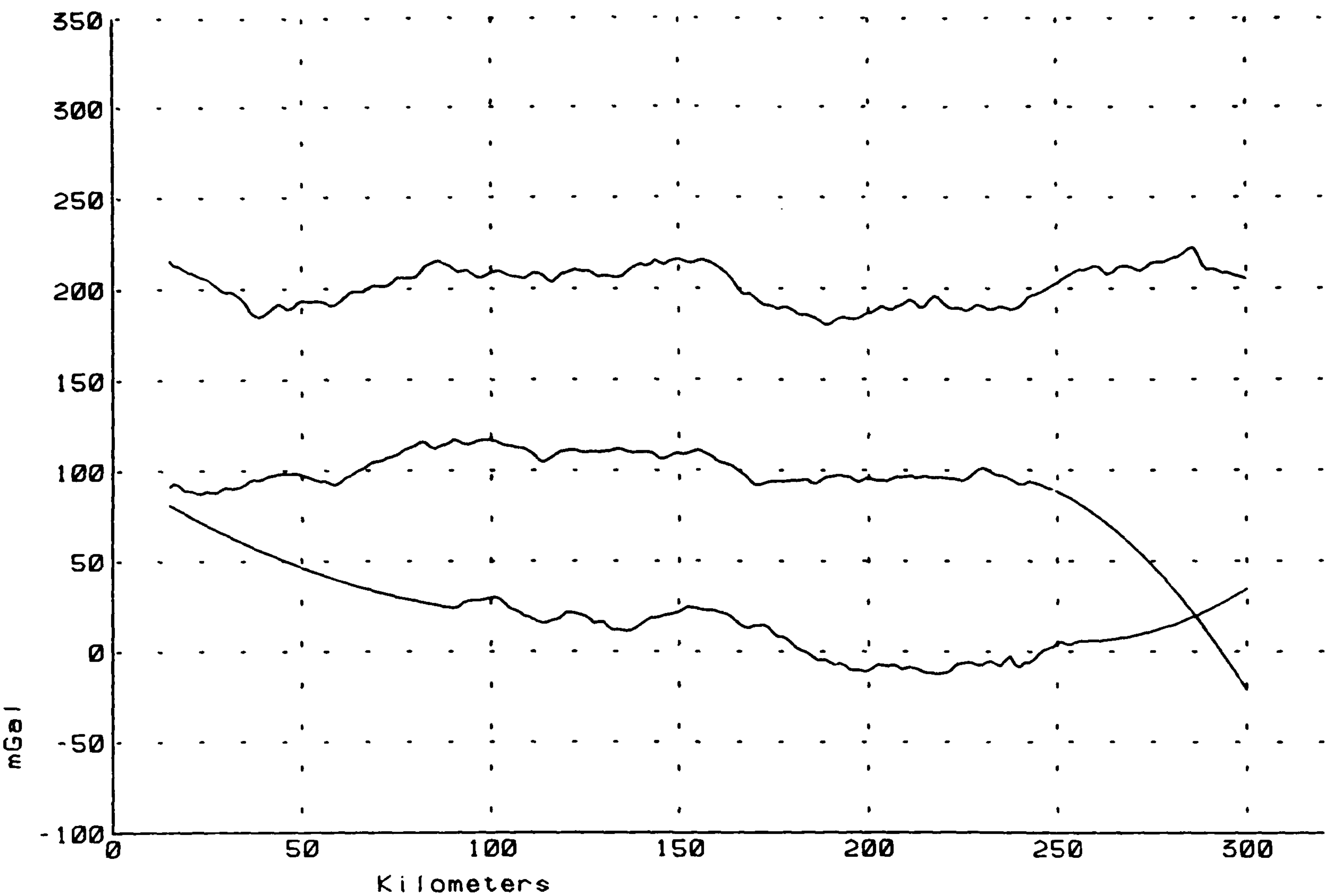


FLIGHT #30 EW T61 GI123 (COMPENSATED)

FIGURE 48



27-MAY-87 14:37
1500.
1125.
750.
375.
0.
-100.532
-99.658
-98.784
-97.909
-97.035
EOTVOS (BIASSED)
FLIGHT #30 EW T61 GC123 (COMPENSATED)



FIG' RE 49

Tz EW 5 6 7

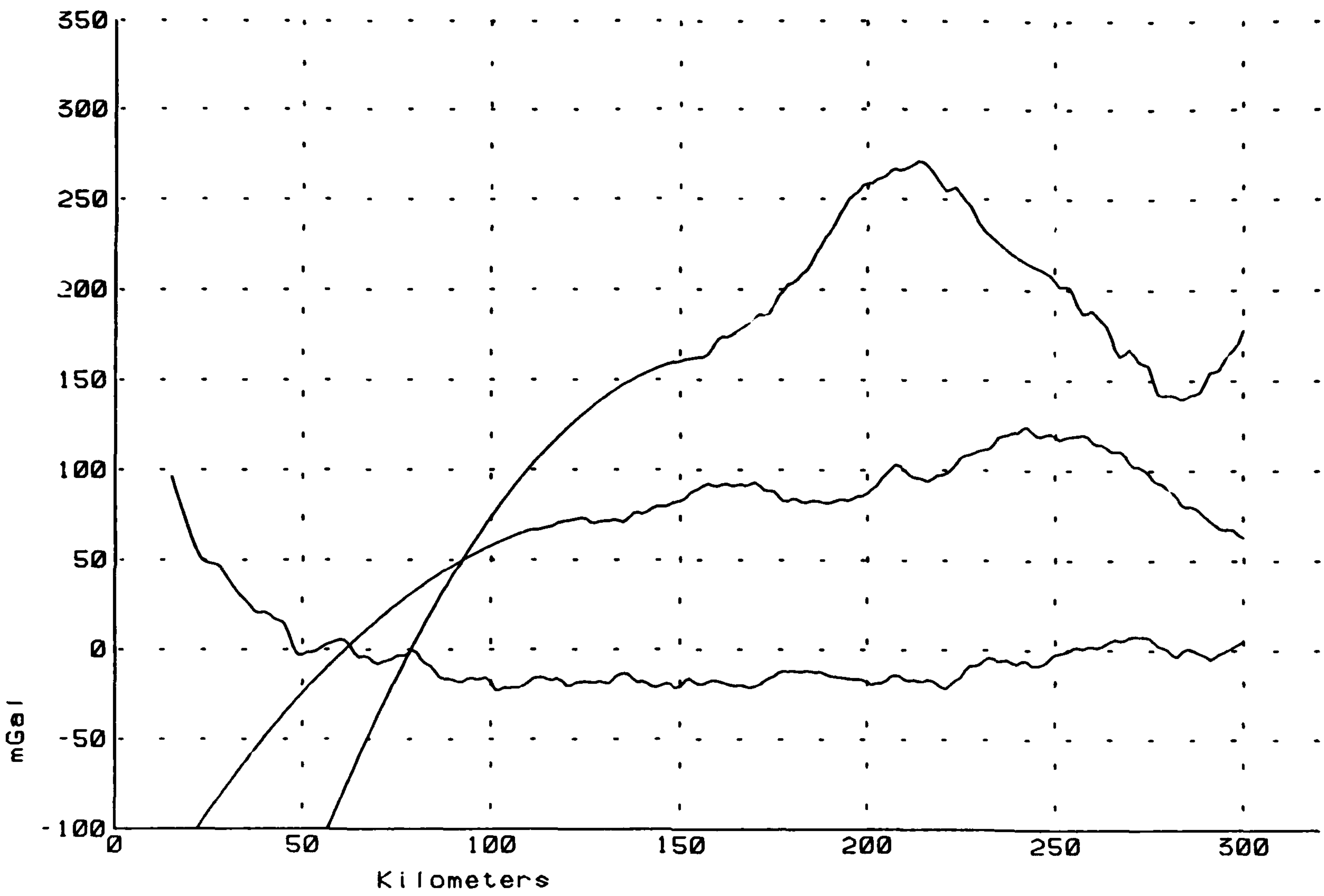


FIGURE 50

Tz EW 12 16 22

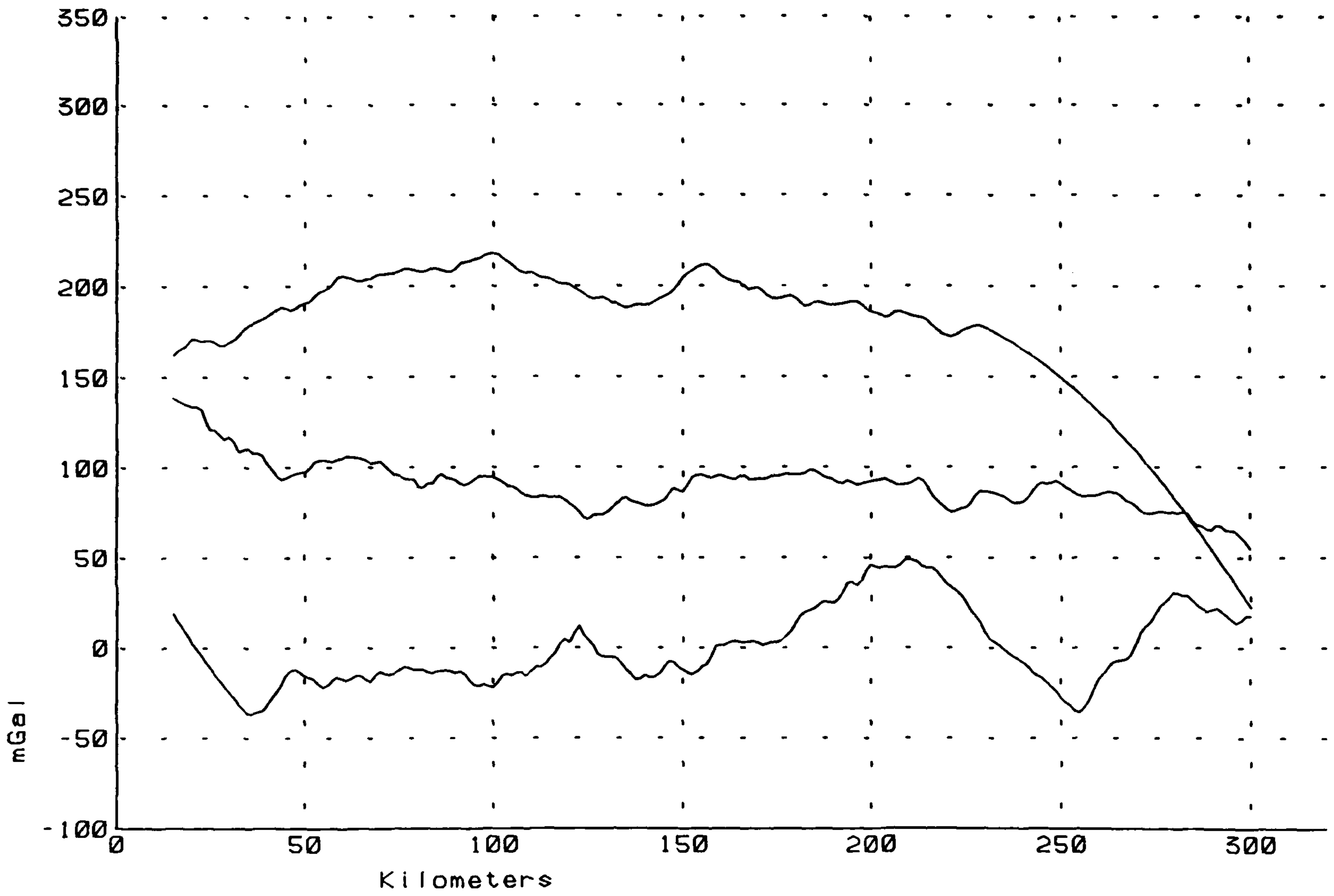


FIGURE 51

Tz EW 26 47 49

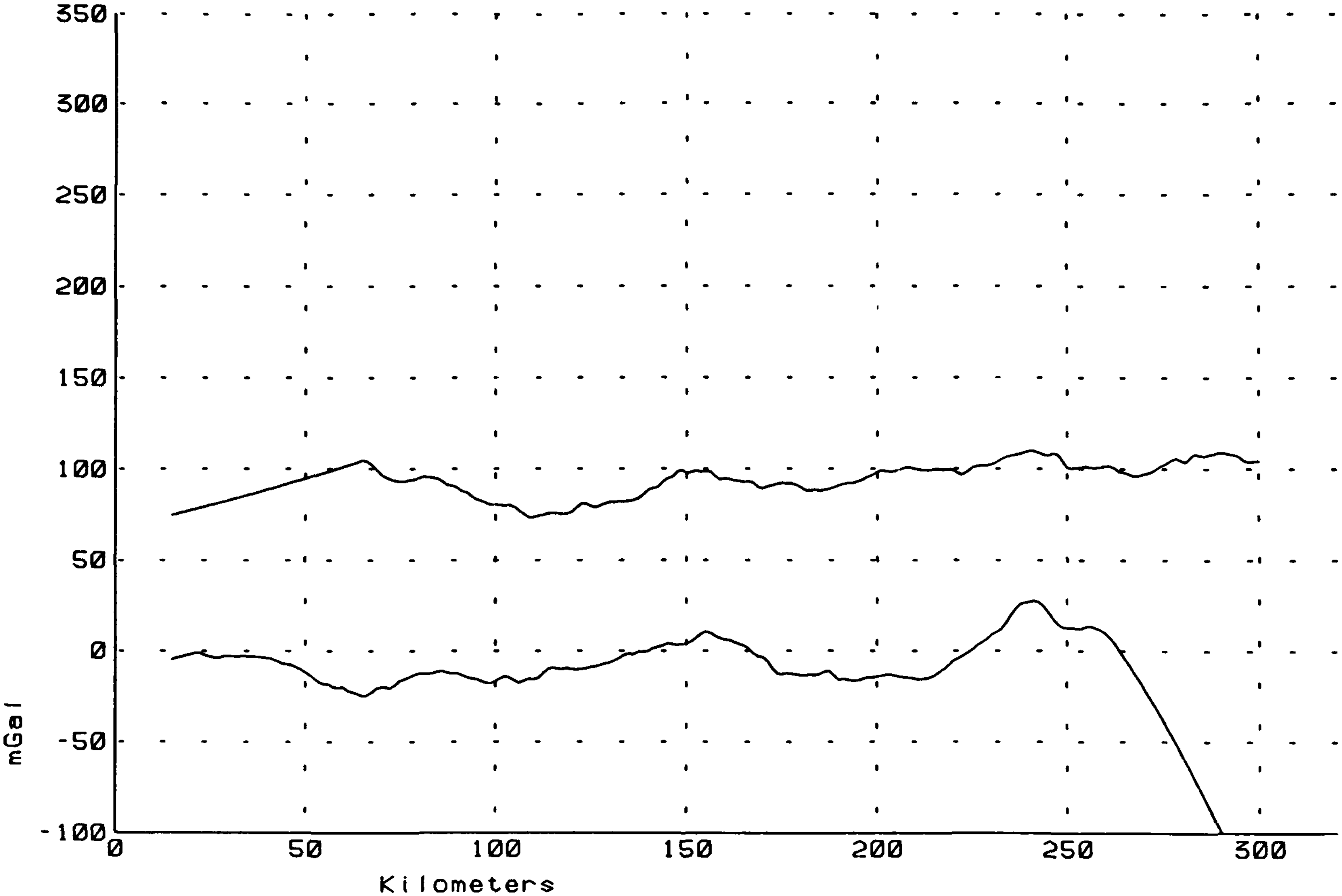


FIGURE 52

Tz EW 53 55

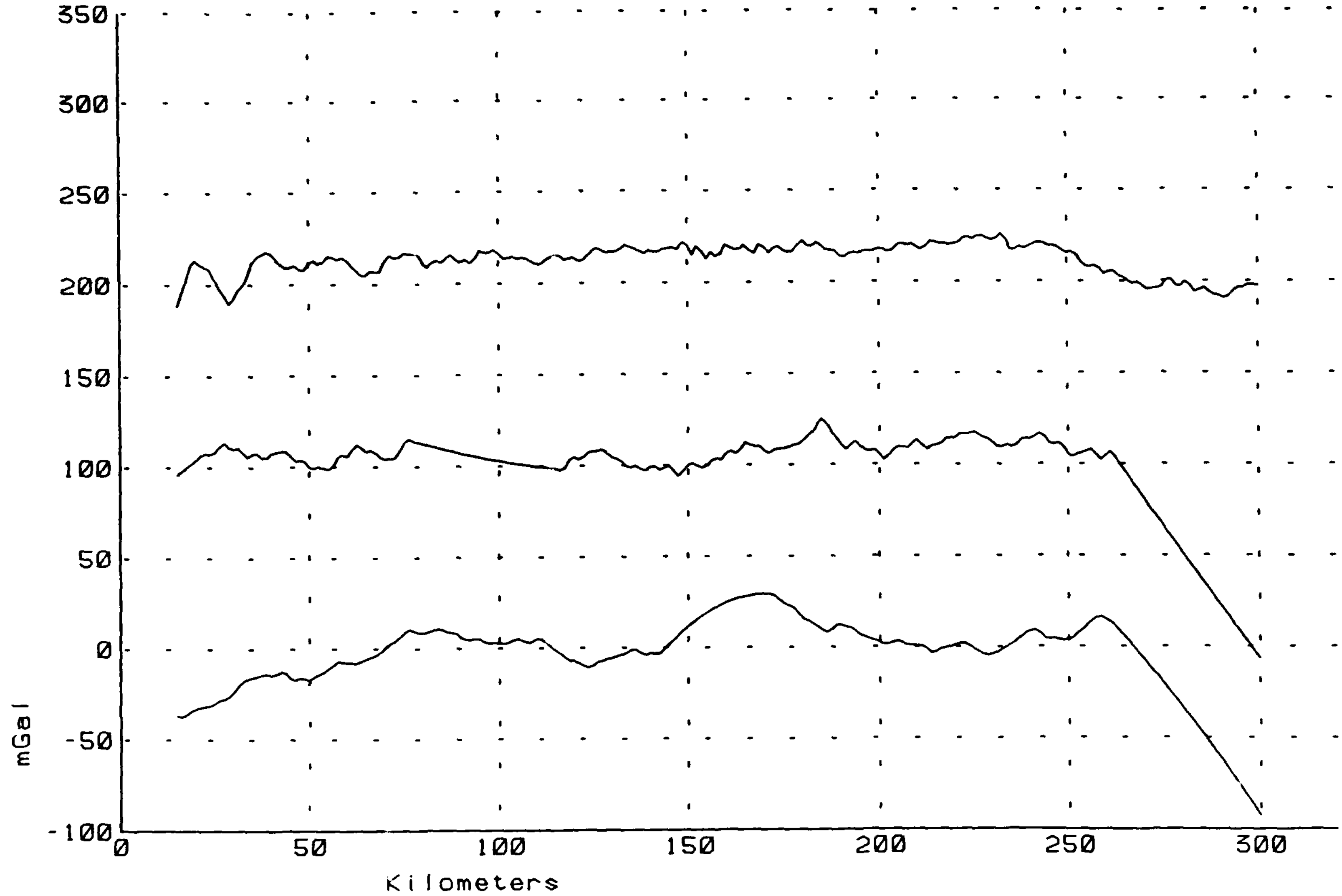


FIGURE 53

Tz EW 57 60 61

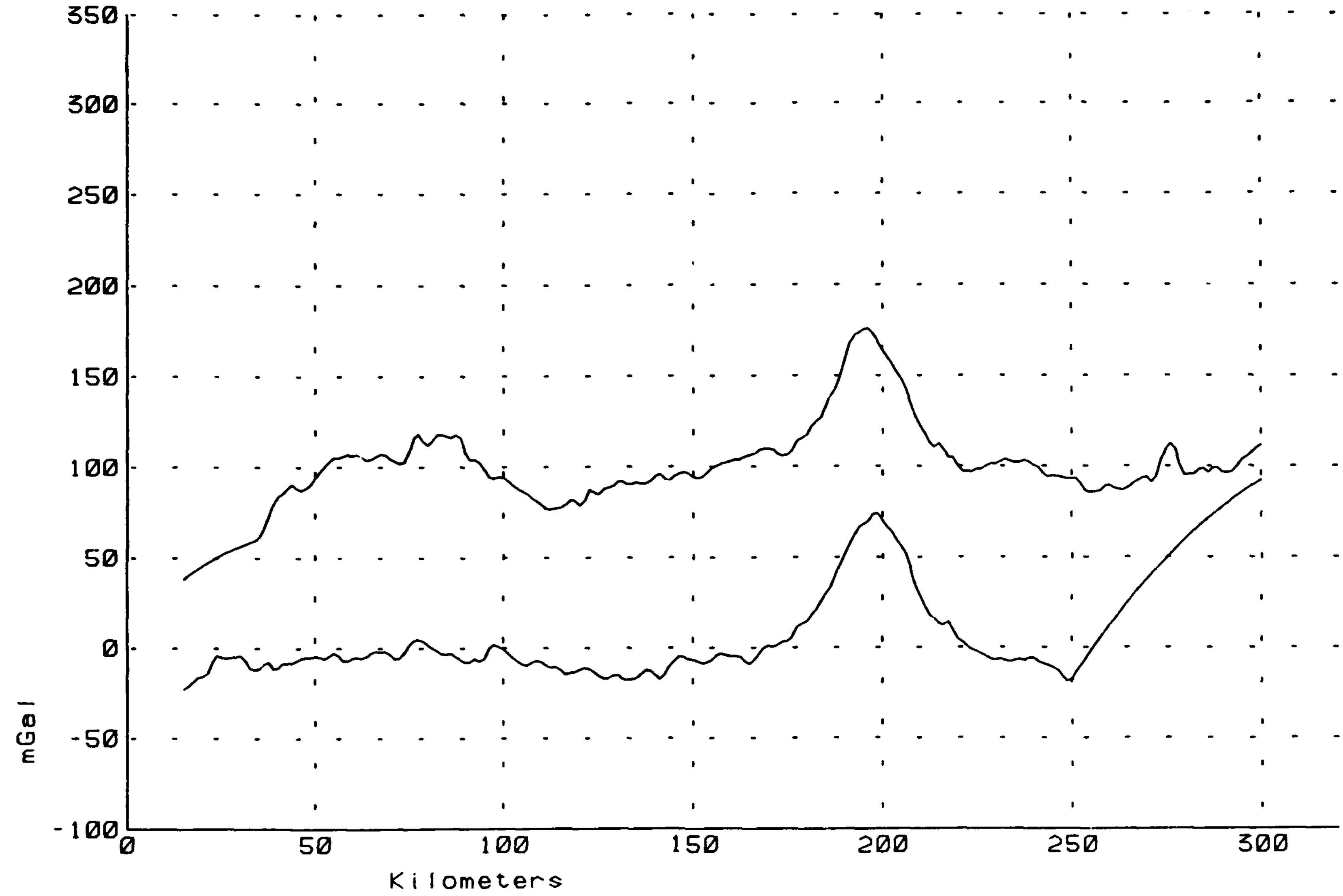


FIGURE 54

Tz NS 11 13

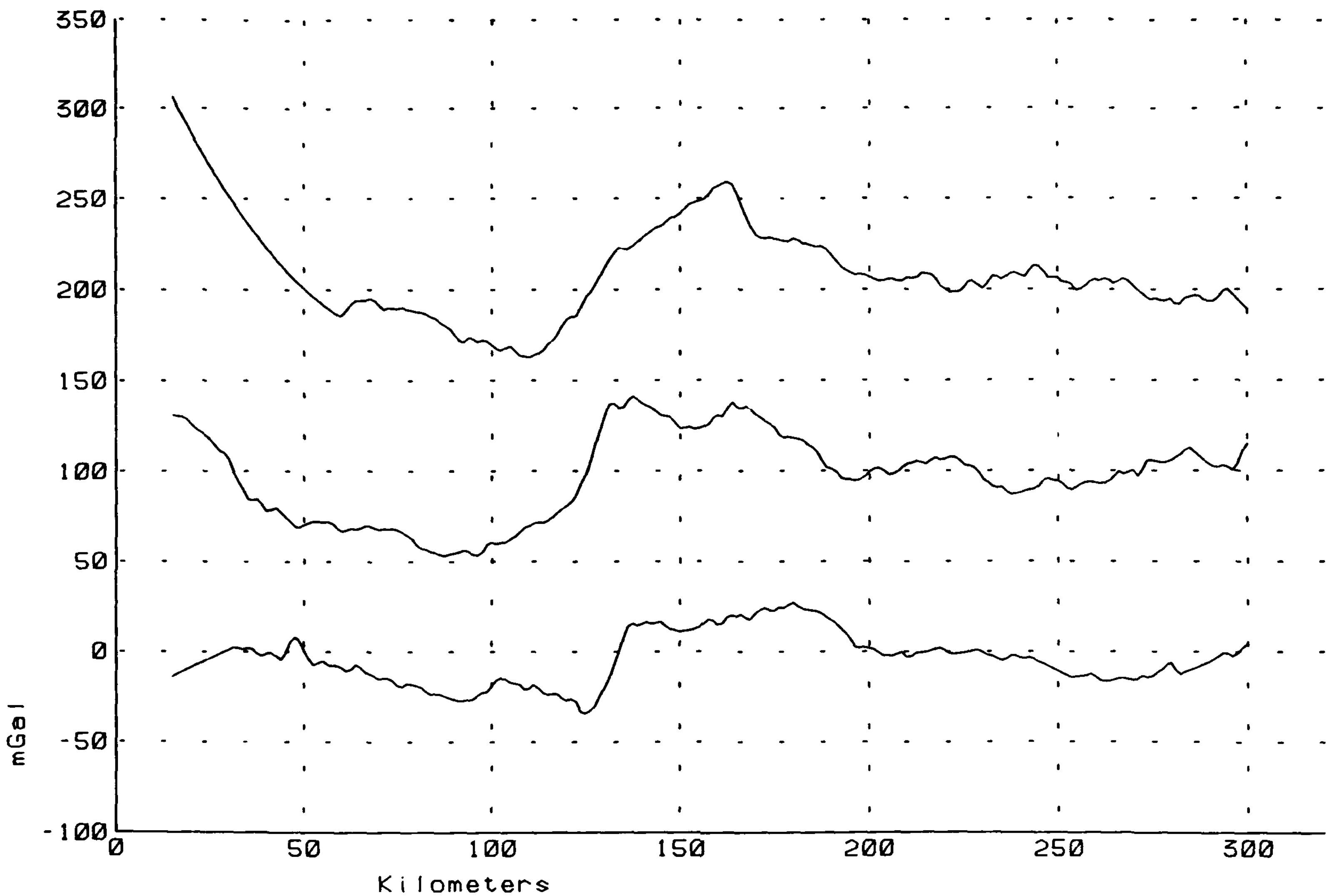


FIGURE 55

Tz NS 28 30 32

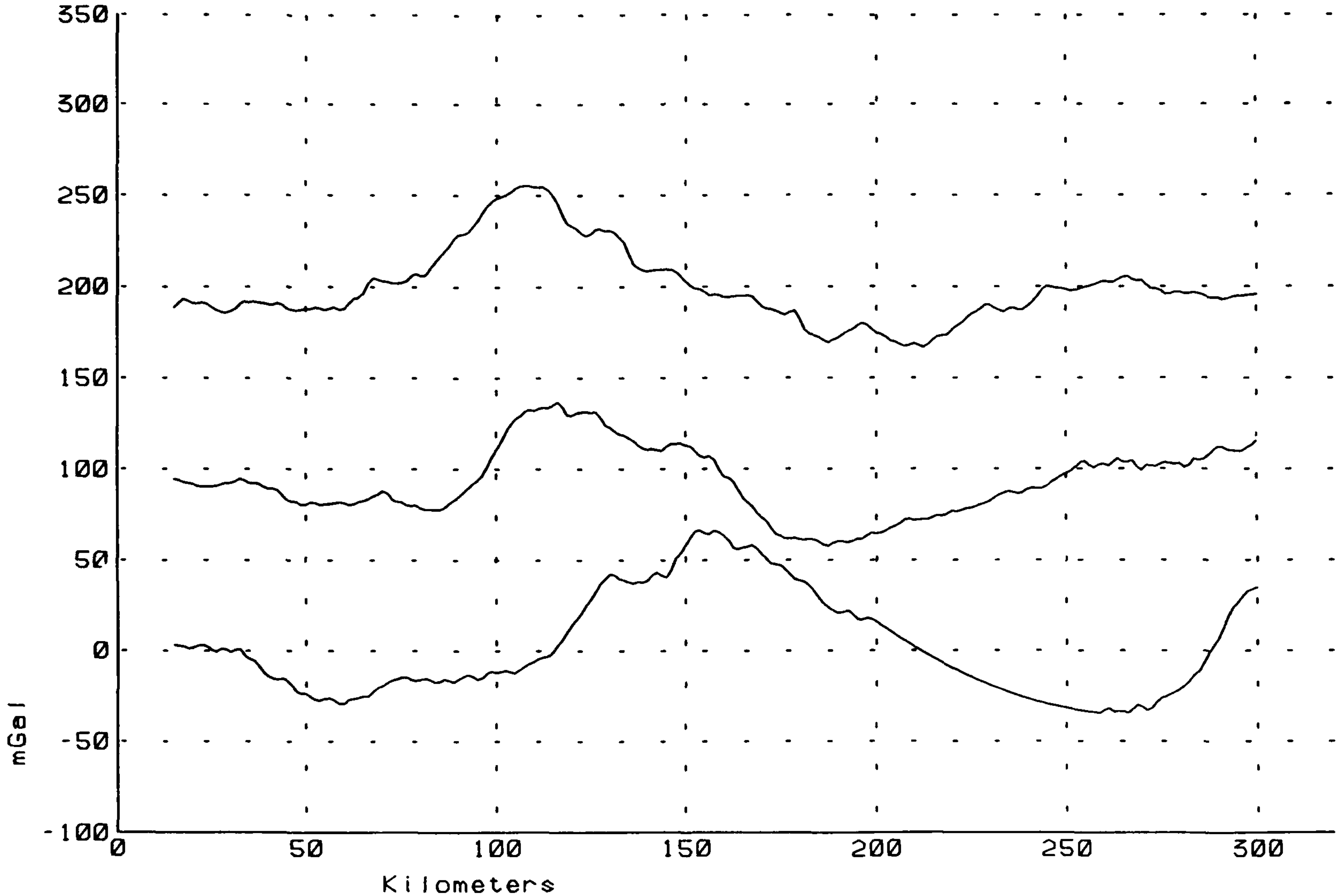


FIGURE 56

Tz NS 35 39 41

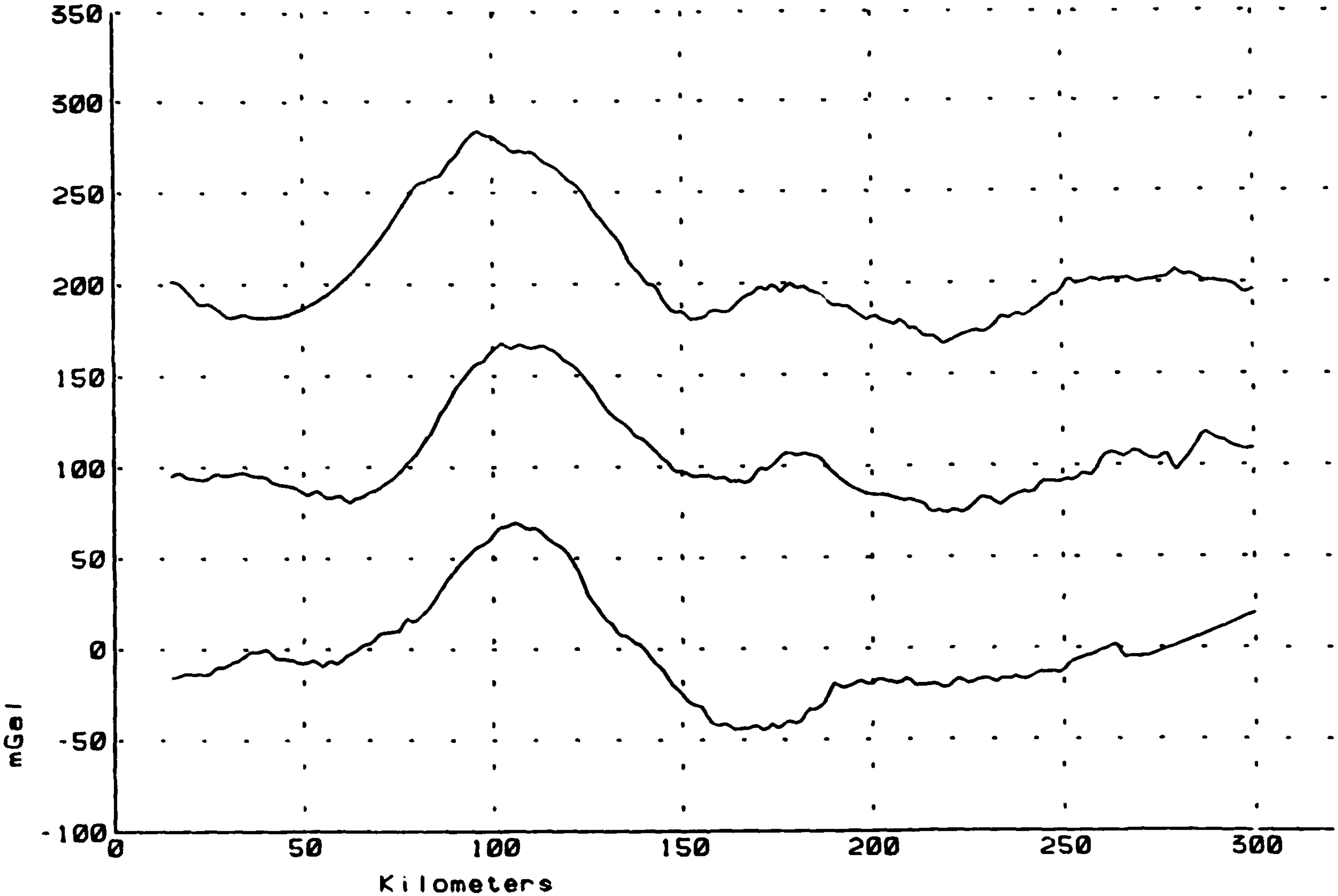


FIGURE 57

Tz NS 42 43 44

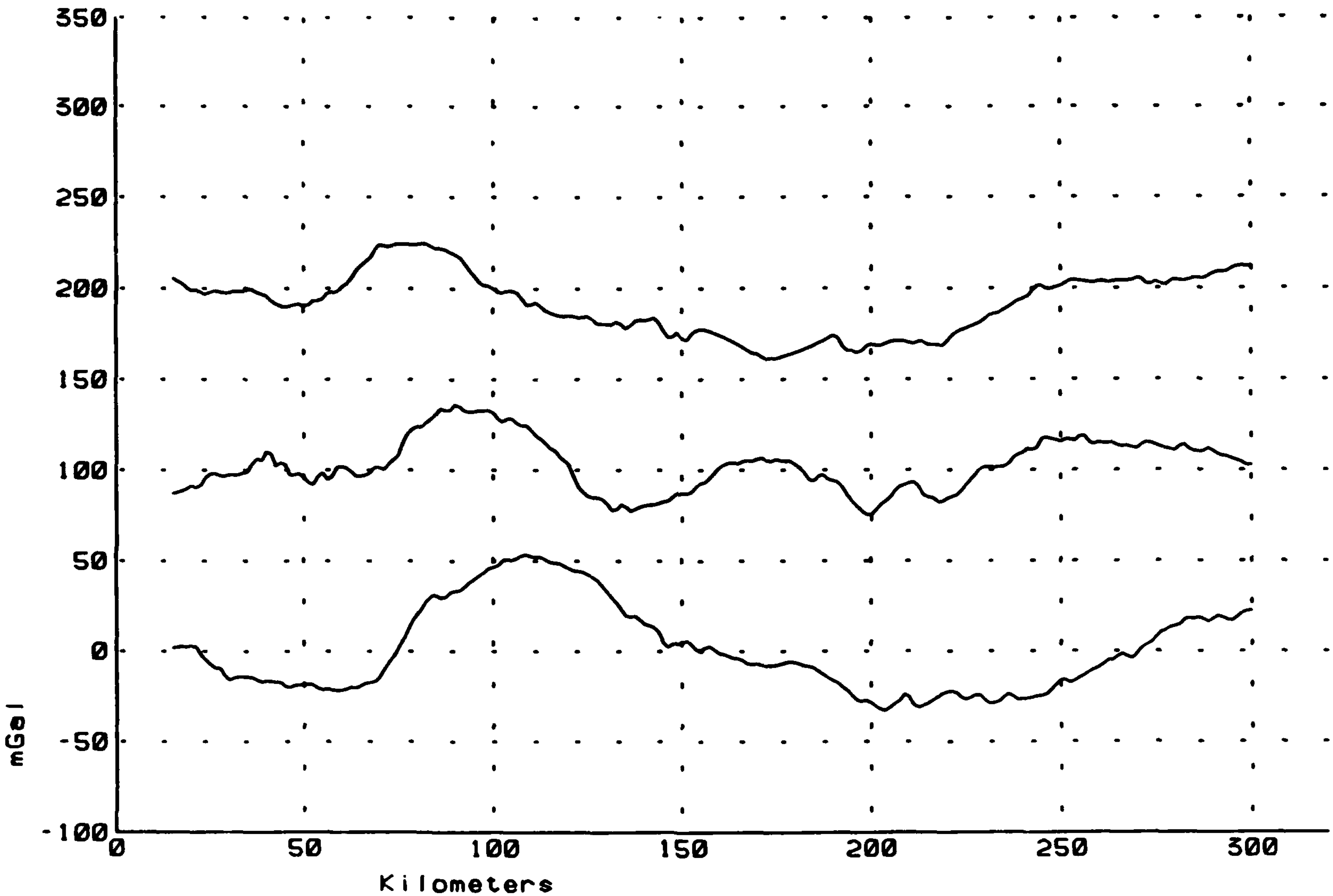


FIGURE 53

Tz NS 46 48 51

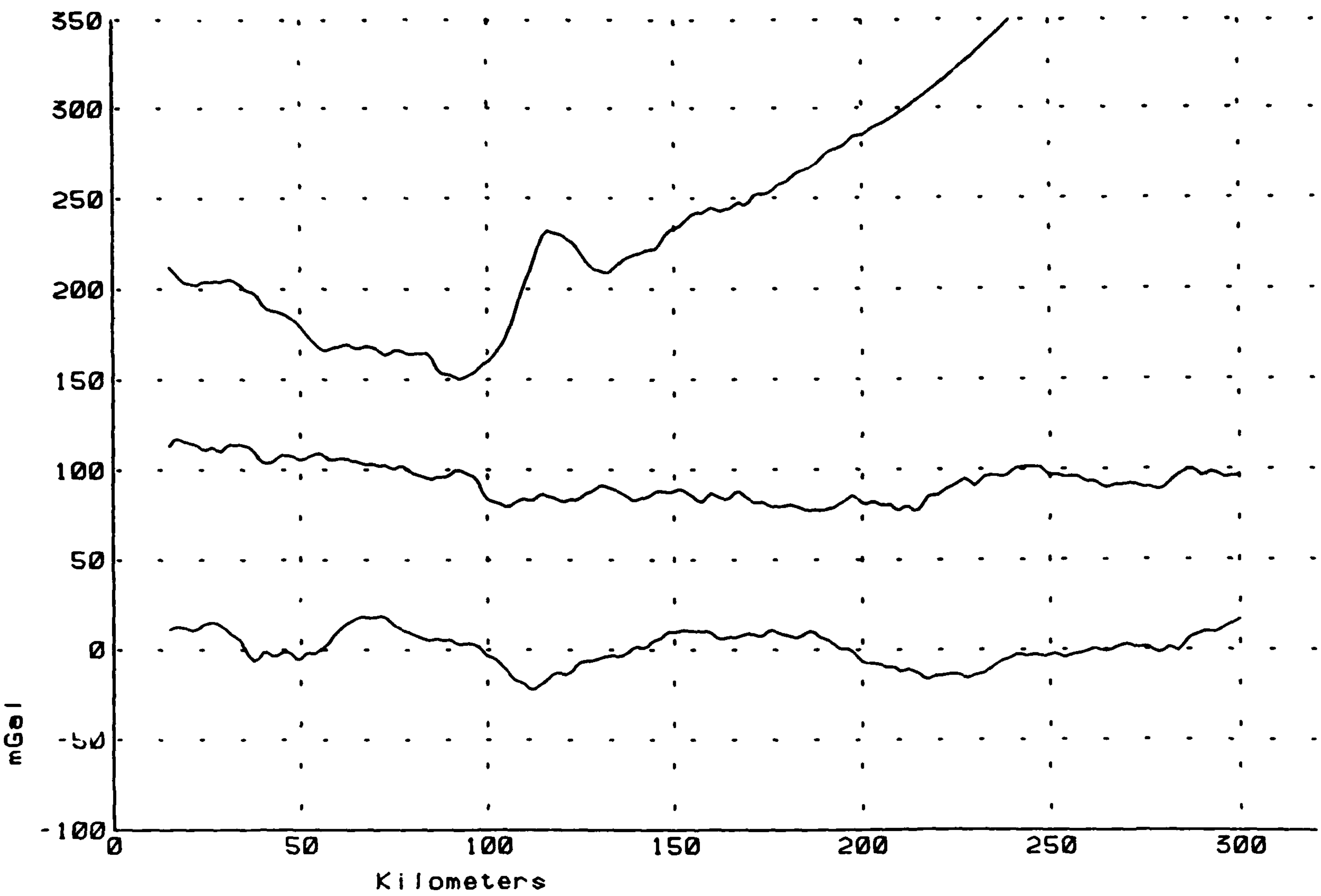


FIGURE 59

Tz NS 53 55 61

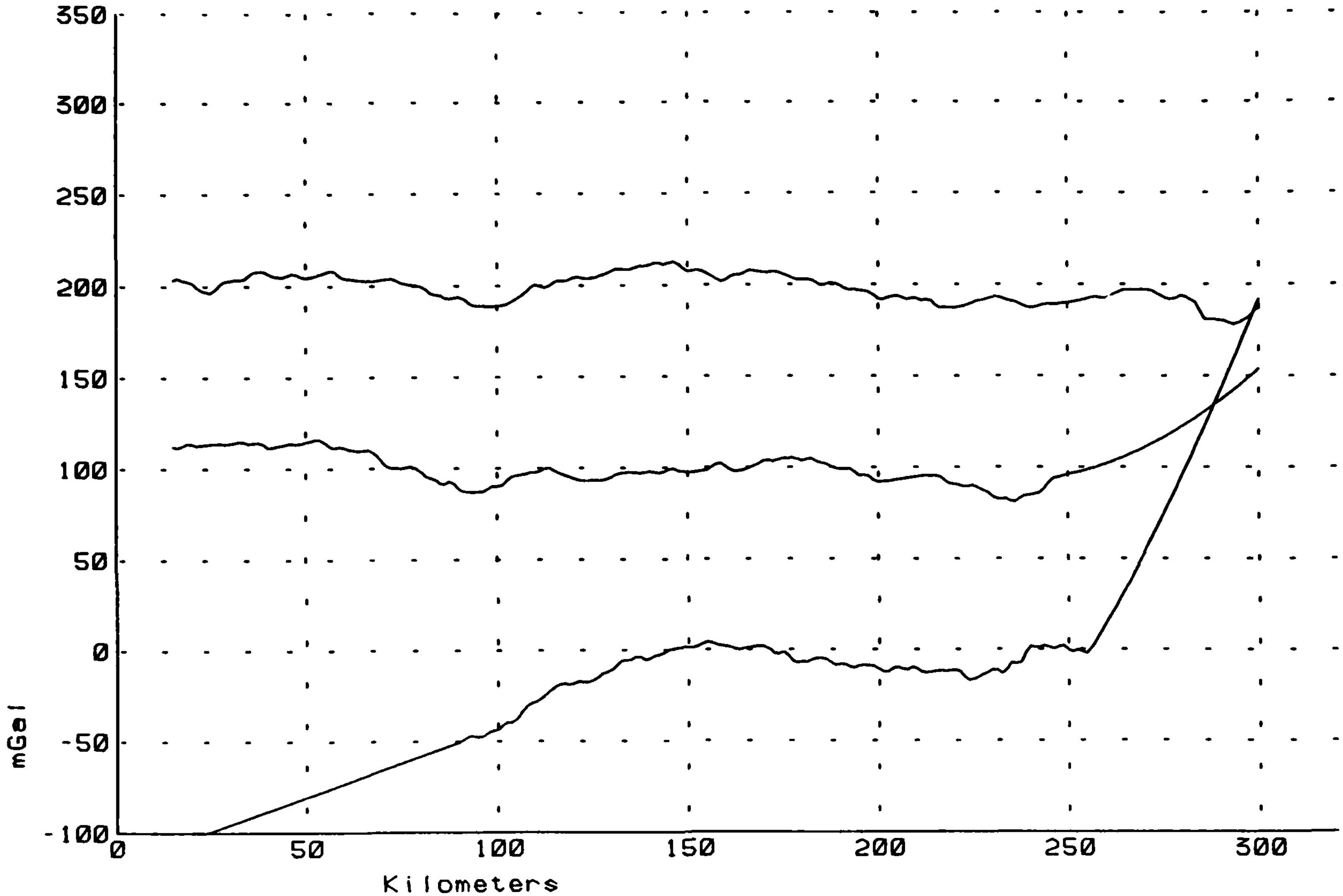


FIGURE 60

Tx EW 5 6 7

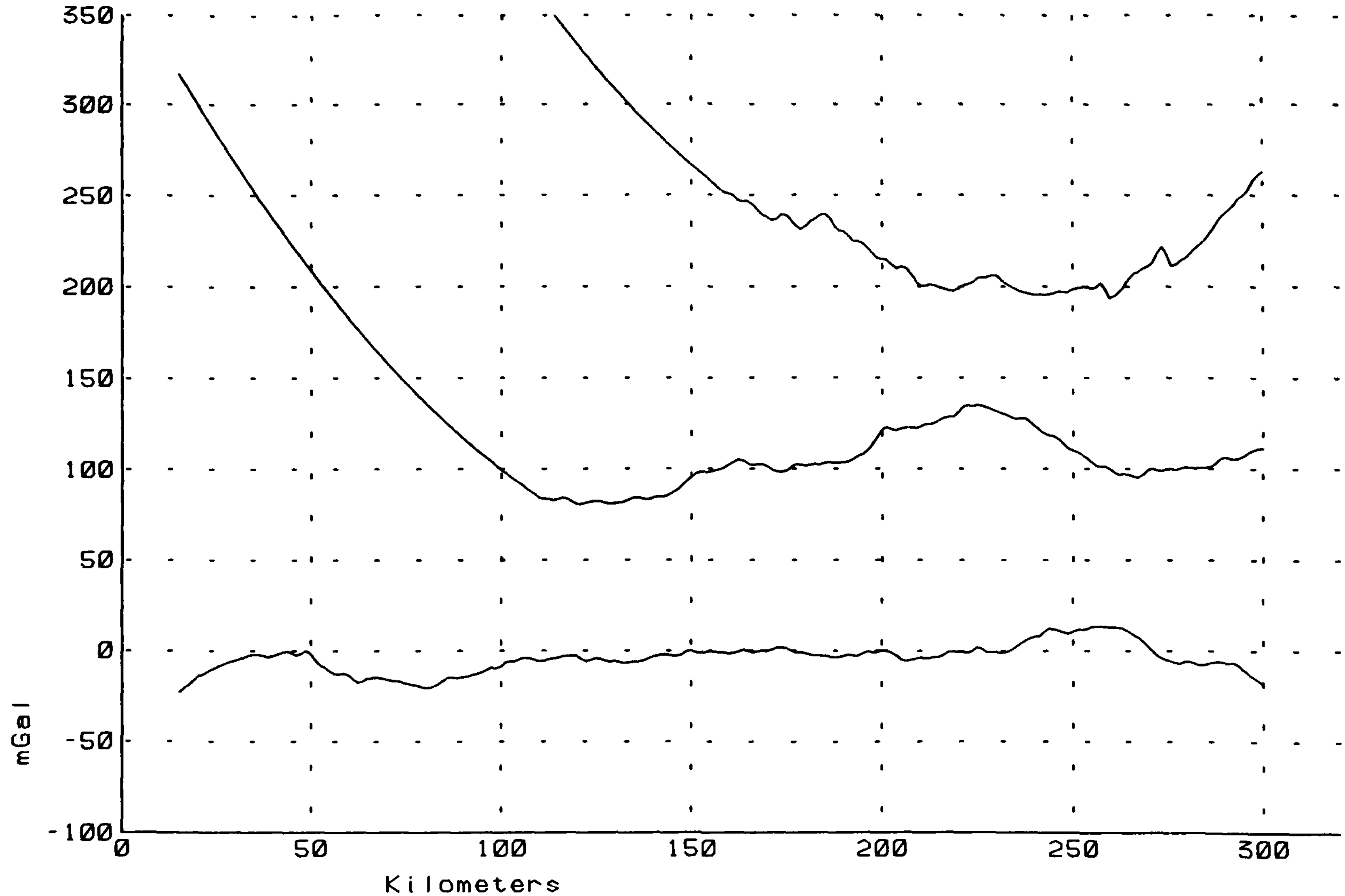


FIGURE 61

Tx EW 12 16 22

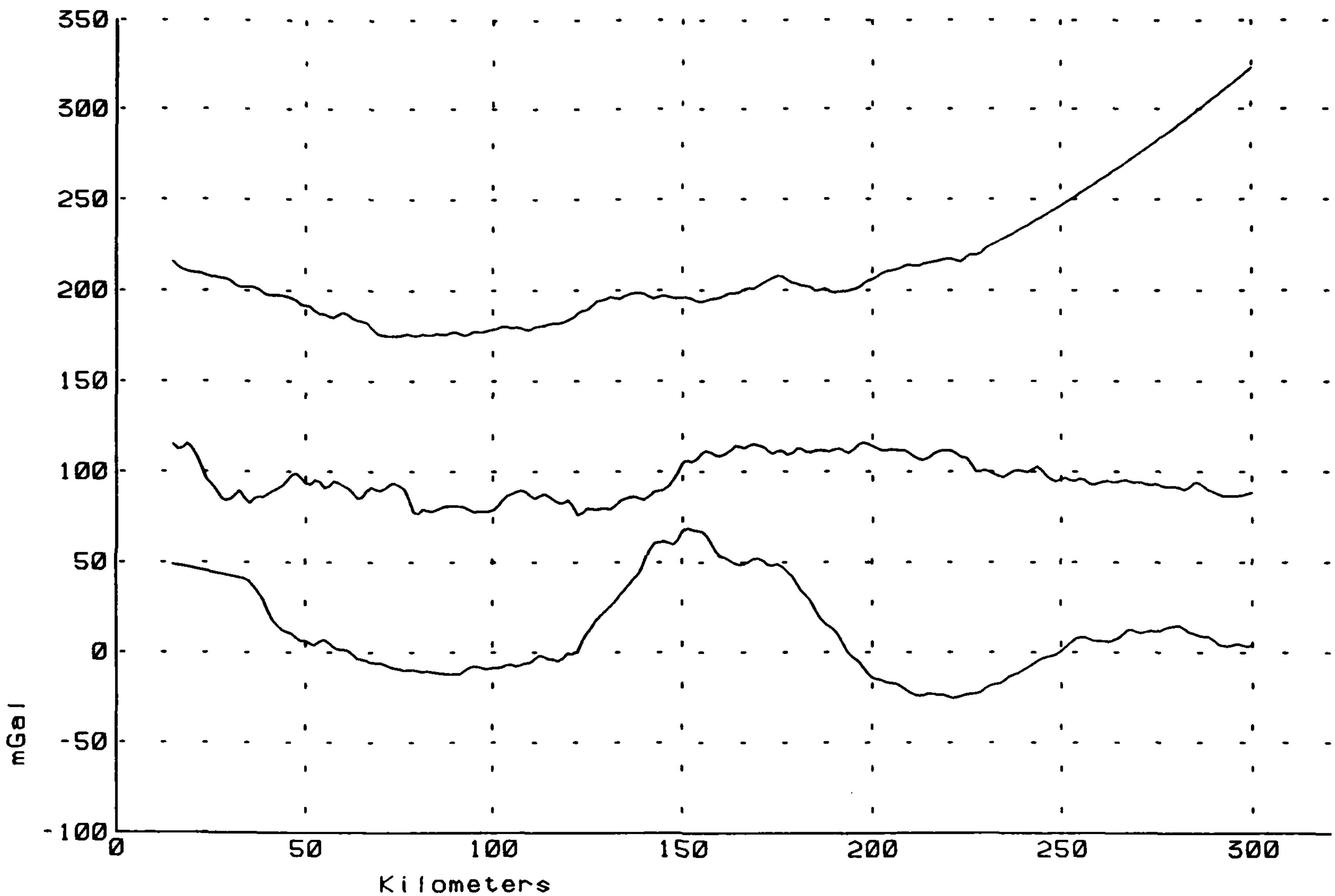


FIGURE 62

Tx EW 26 47 49

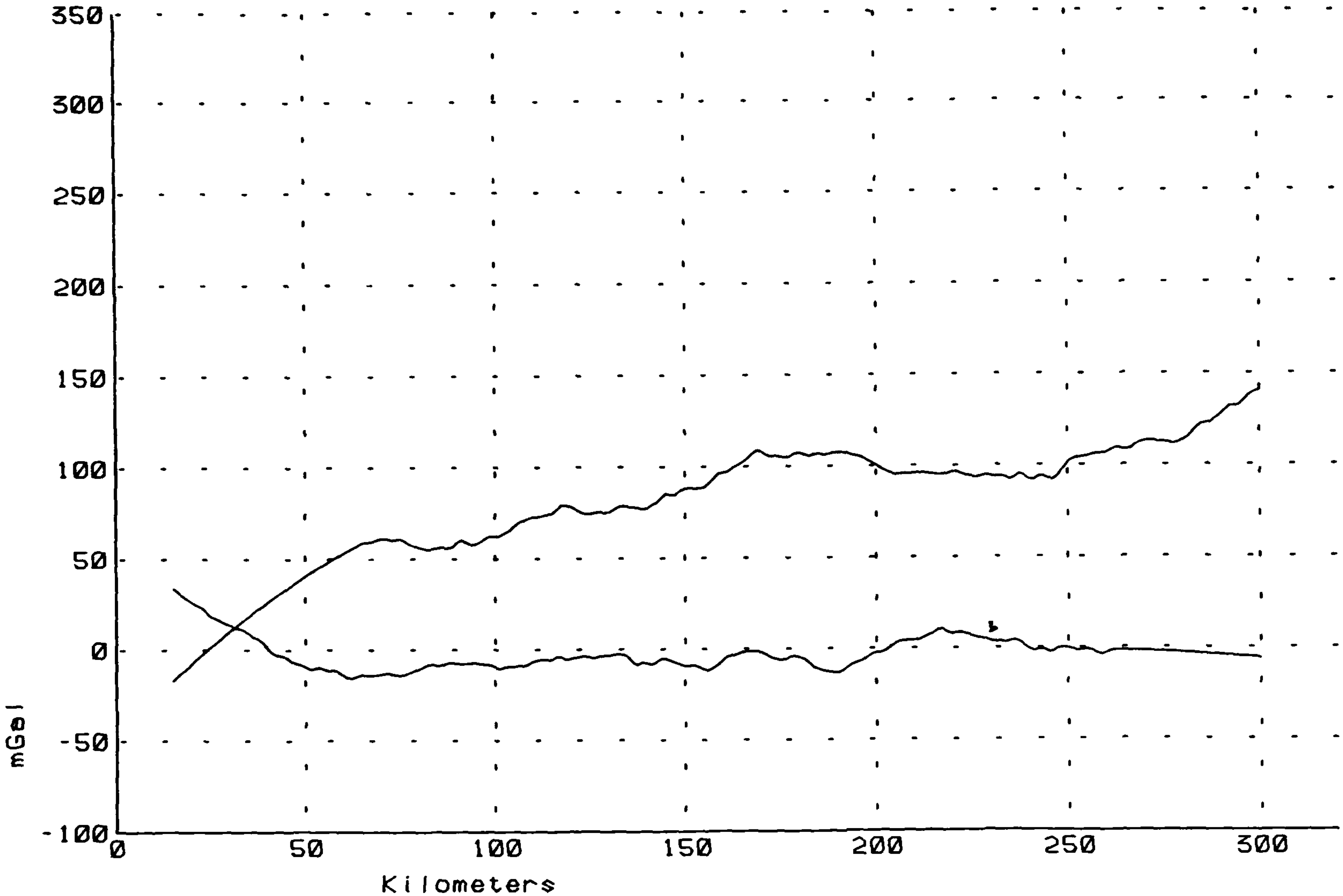


FIGURE 63

Tx EW 53 55

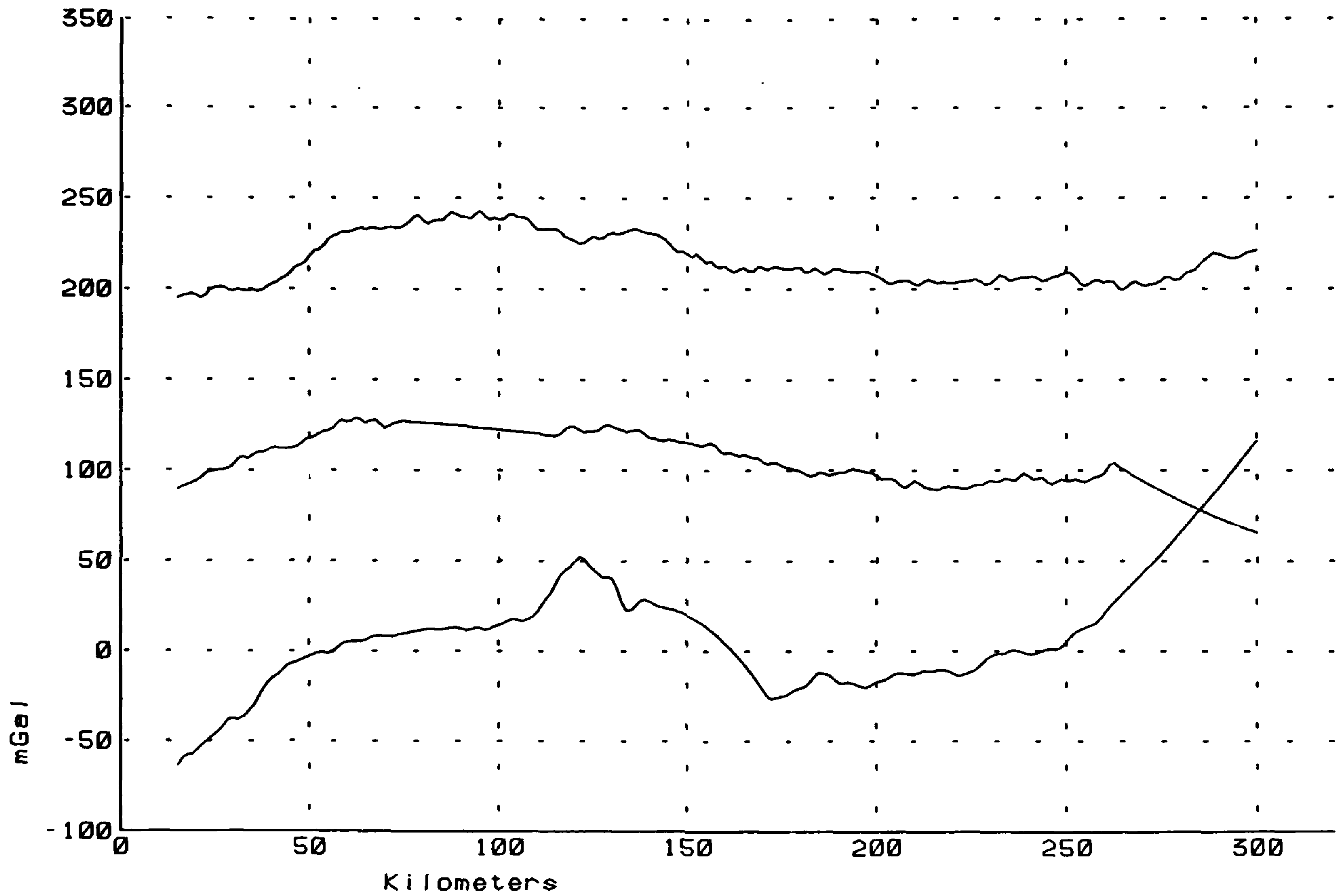


FIGURE 64

Tx EW 57 60 61

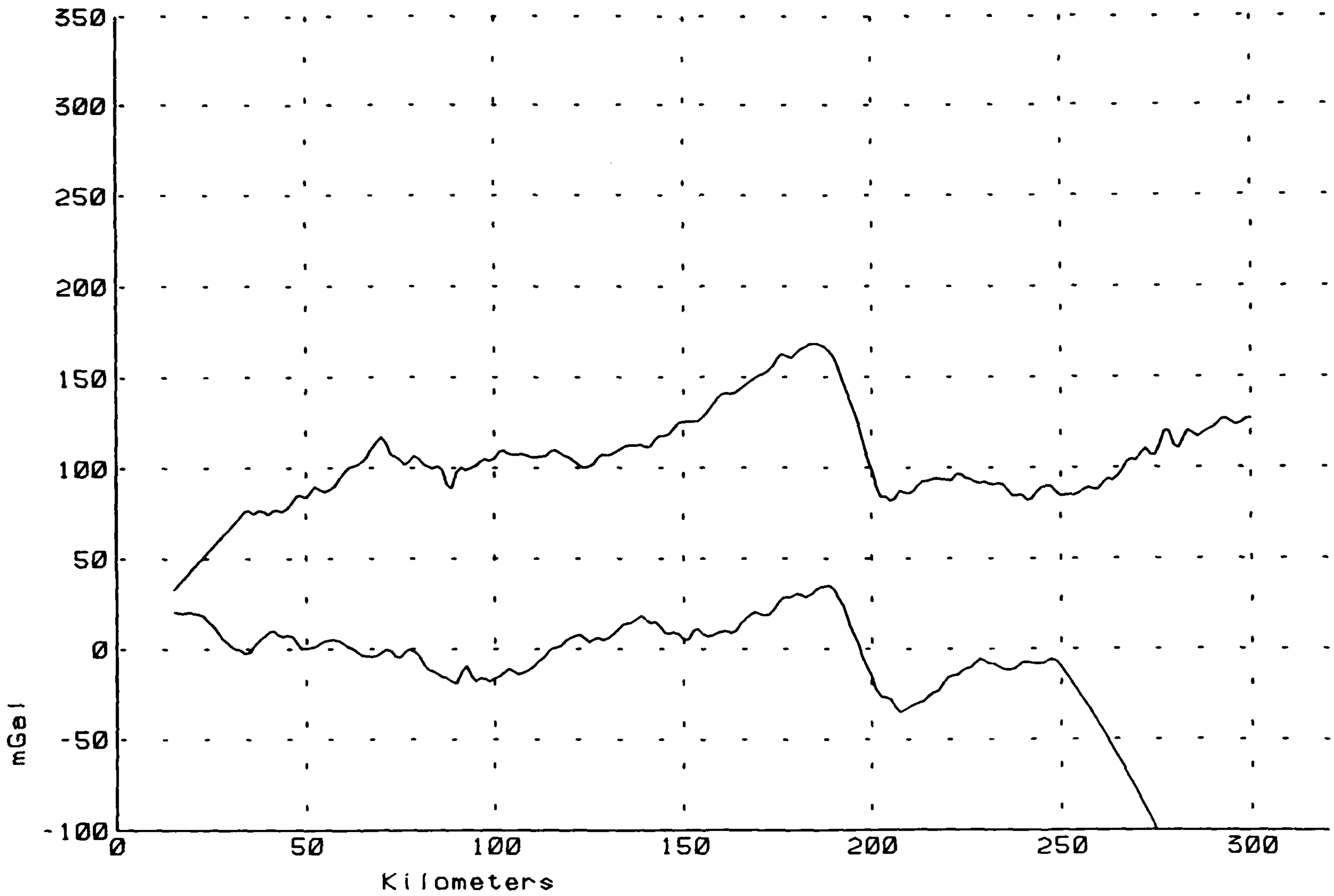


FIGURE 65

Tx NS 11 13

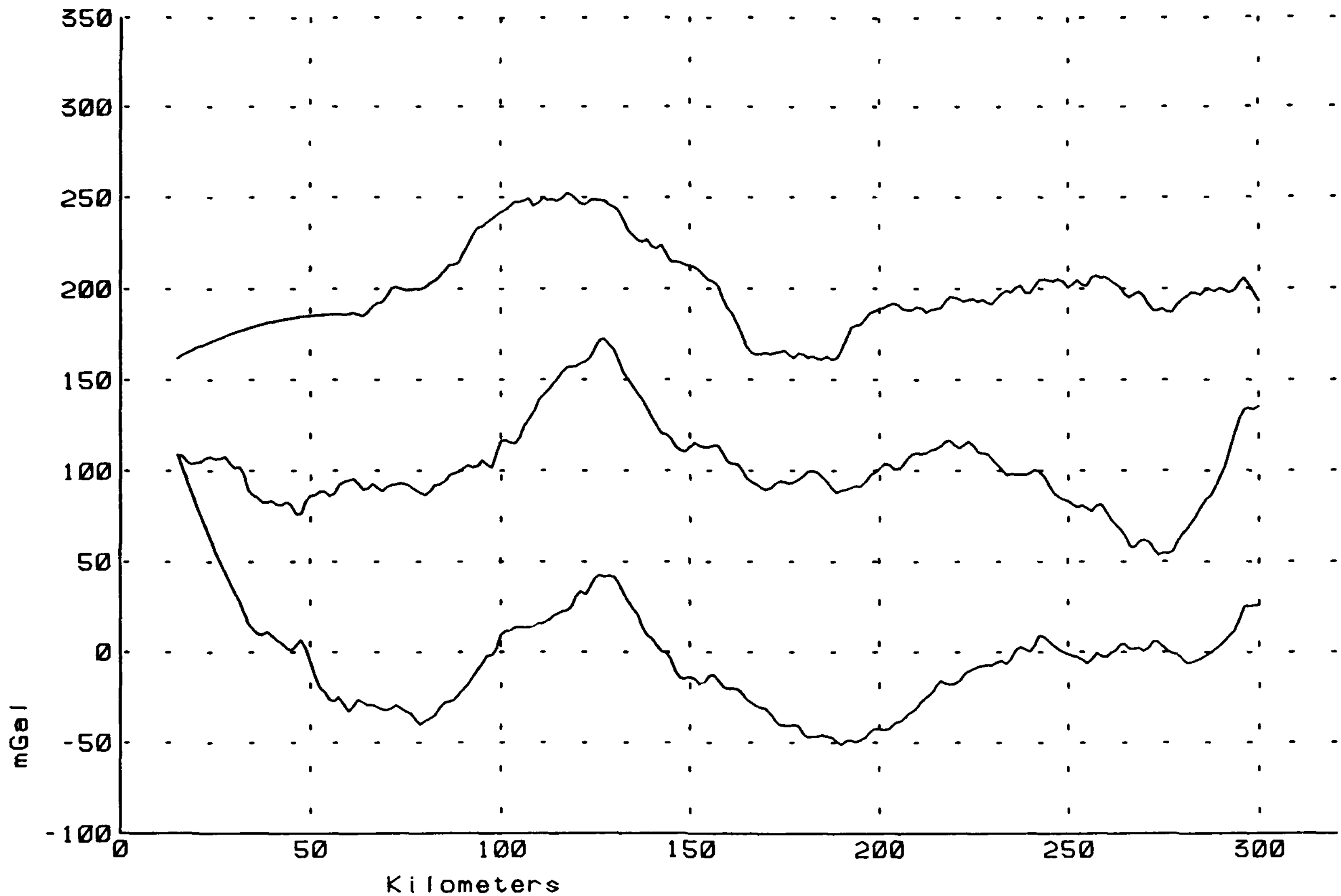


FIGURE 66

Tx NS 28 30 32

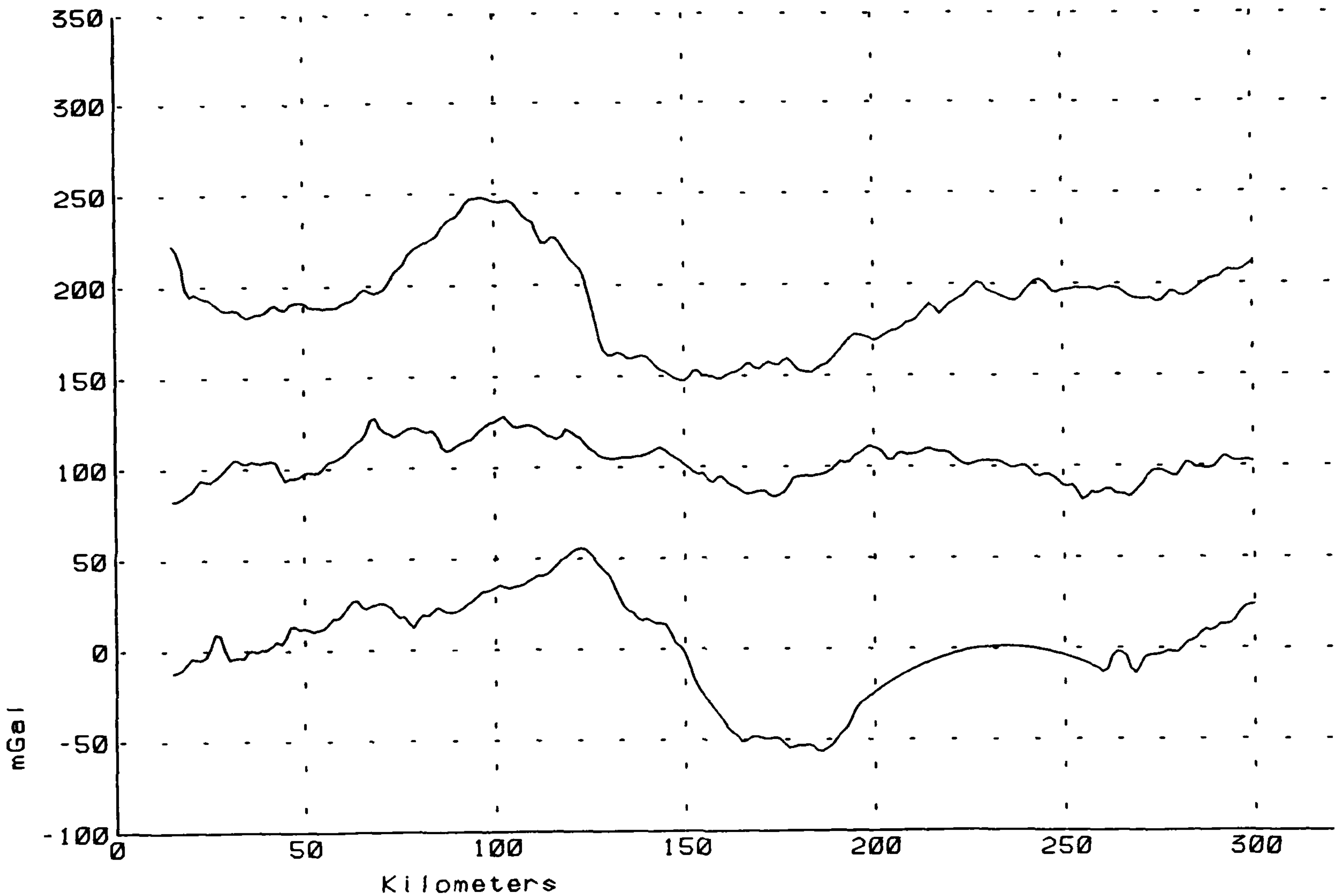


FIGURE 67

Tx NS 35 39 41

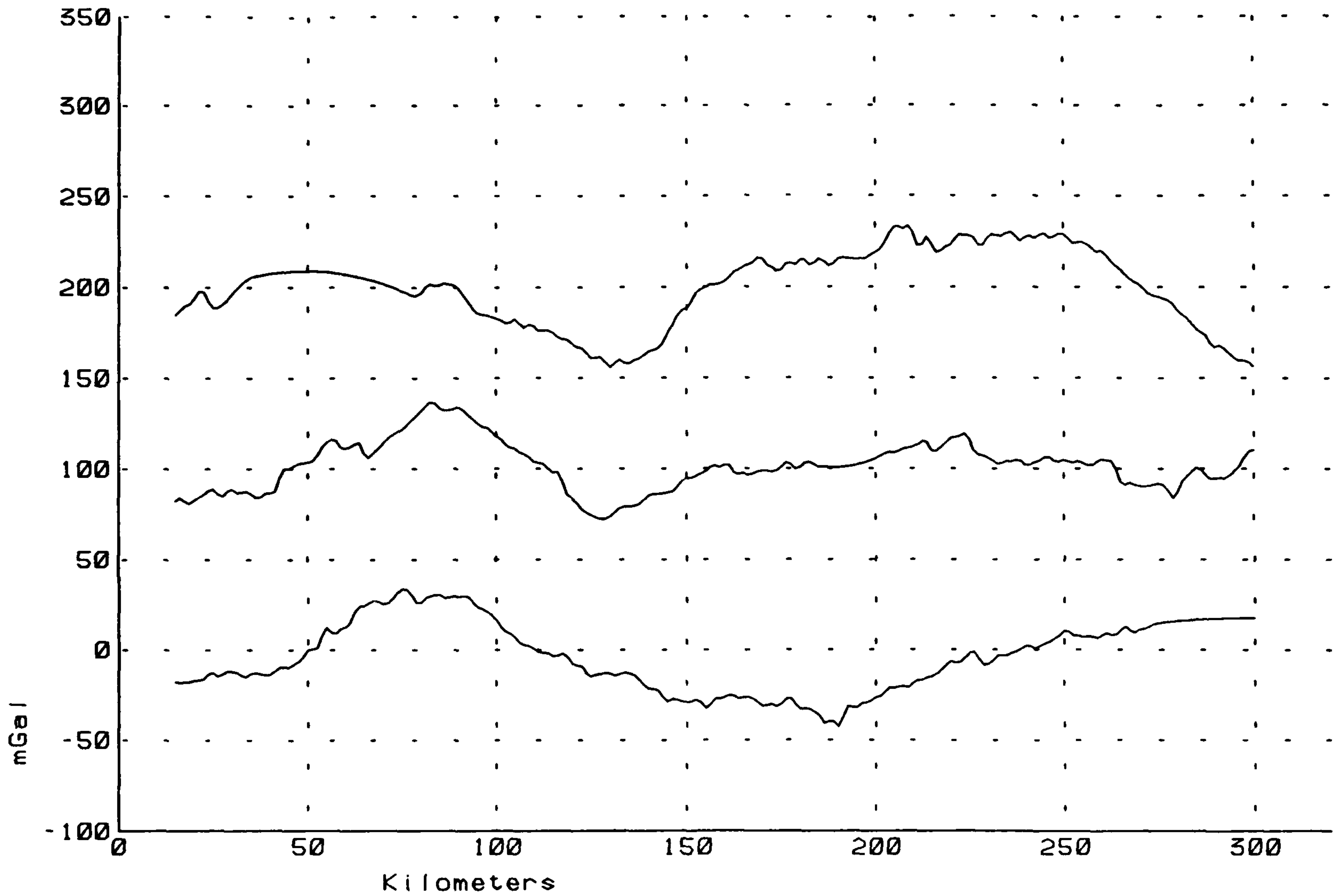


FIGURE 68

Tx NS 42 43 44

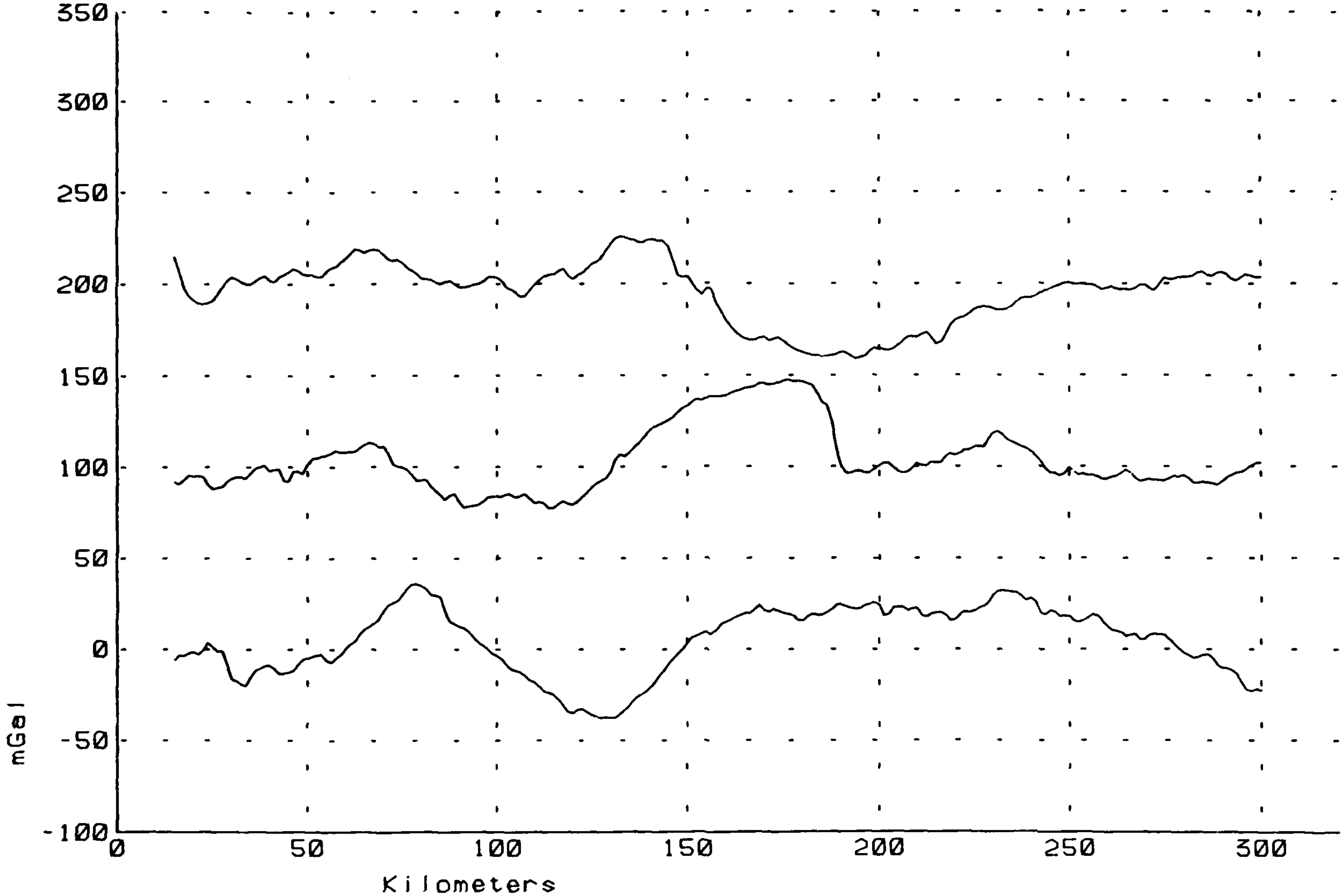


FIGURE 69

Tx NS 46 48 51

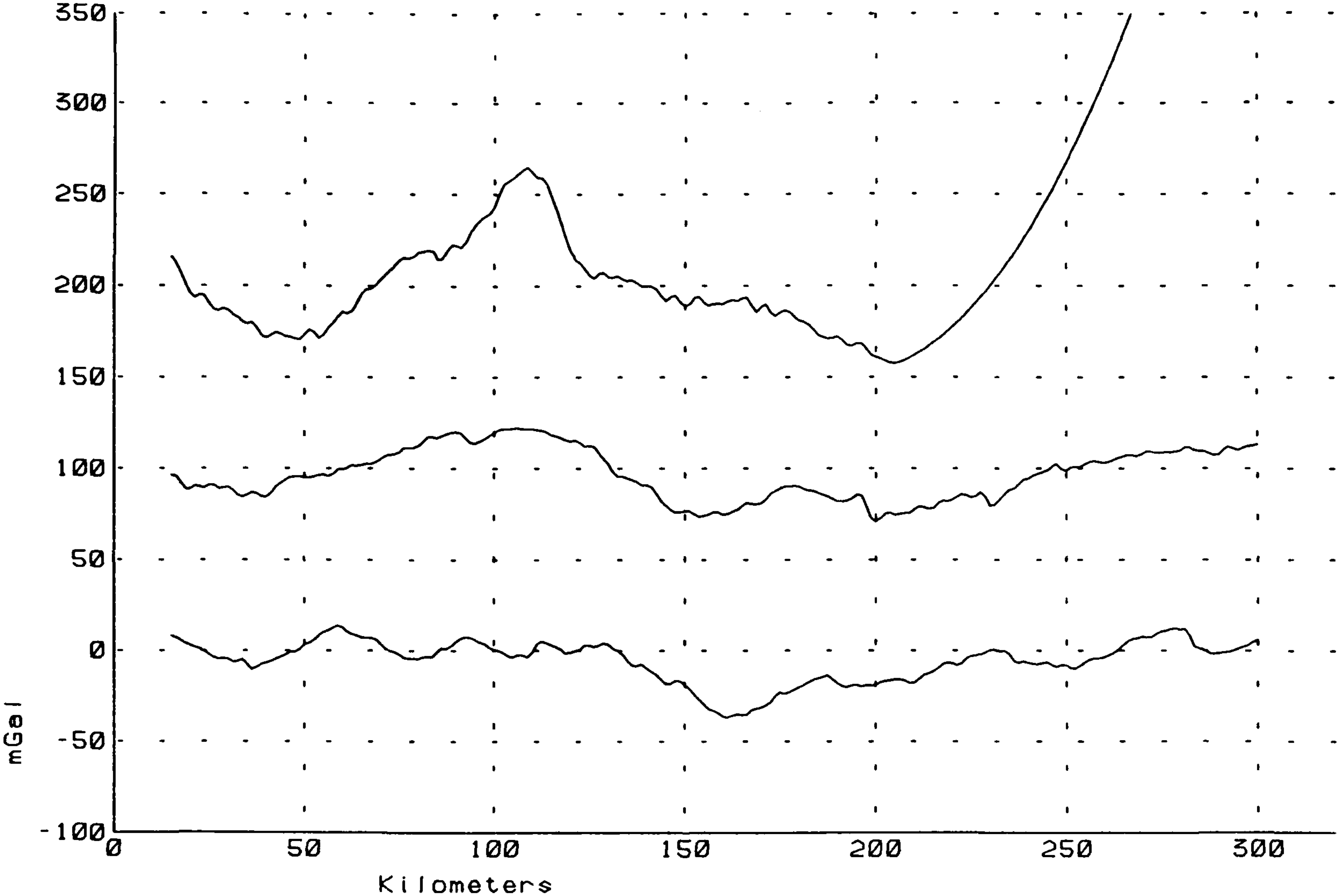


FIGURE 70

Tx NS 53 55 61

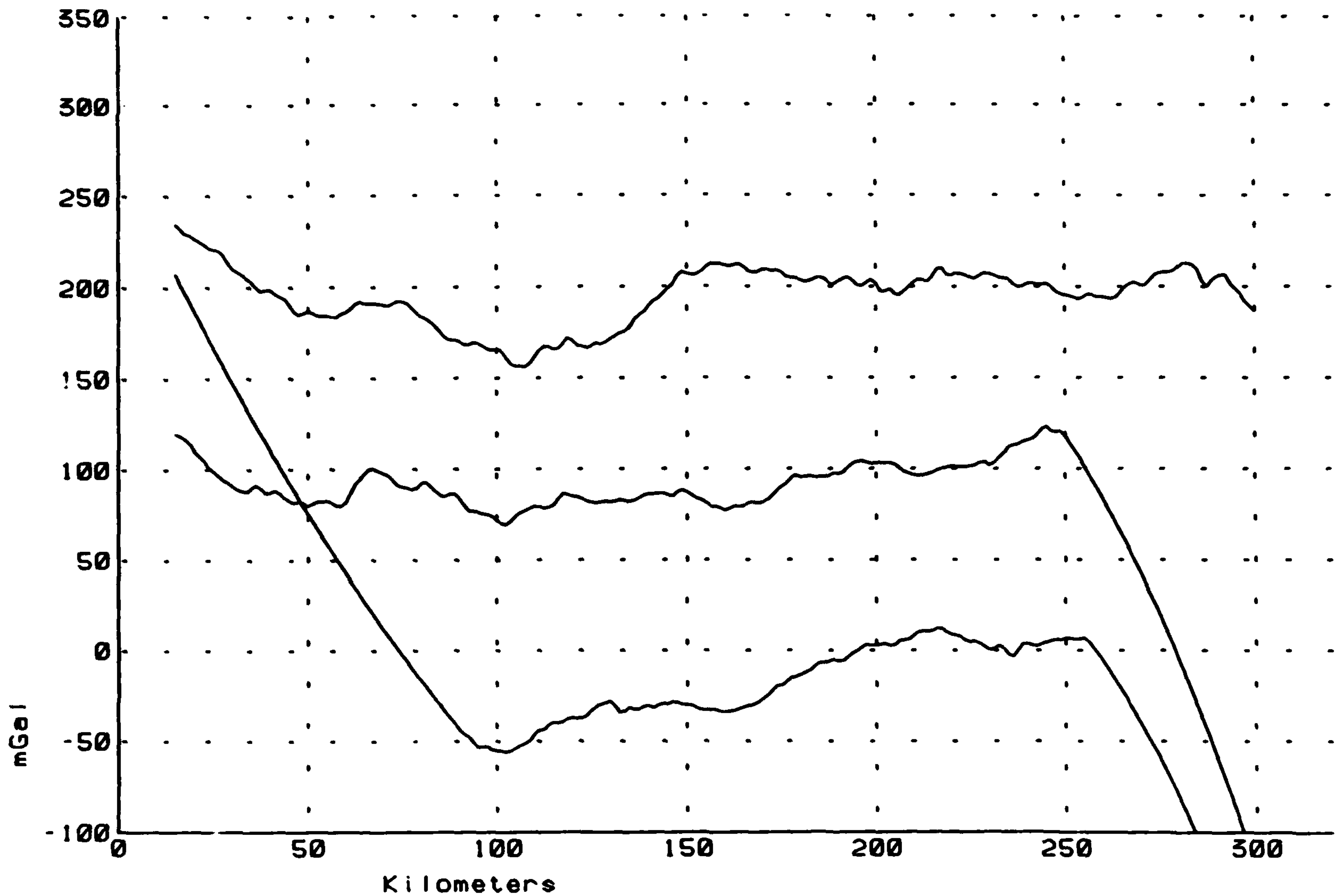


FIGURE 71

Ty EW 5 6 7

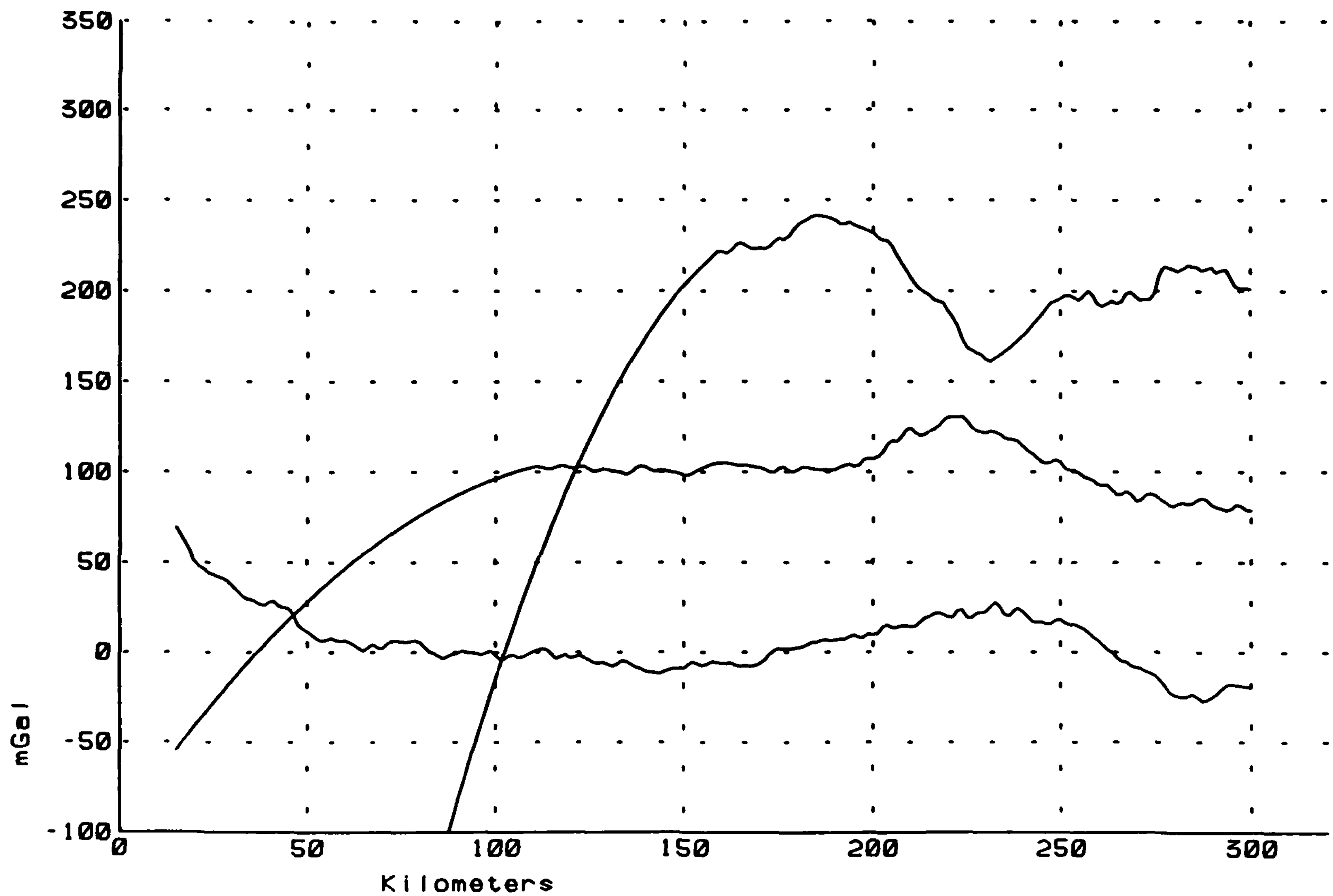


FIGURE 72

Ty EW 12 16 22

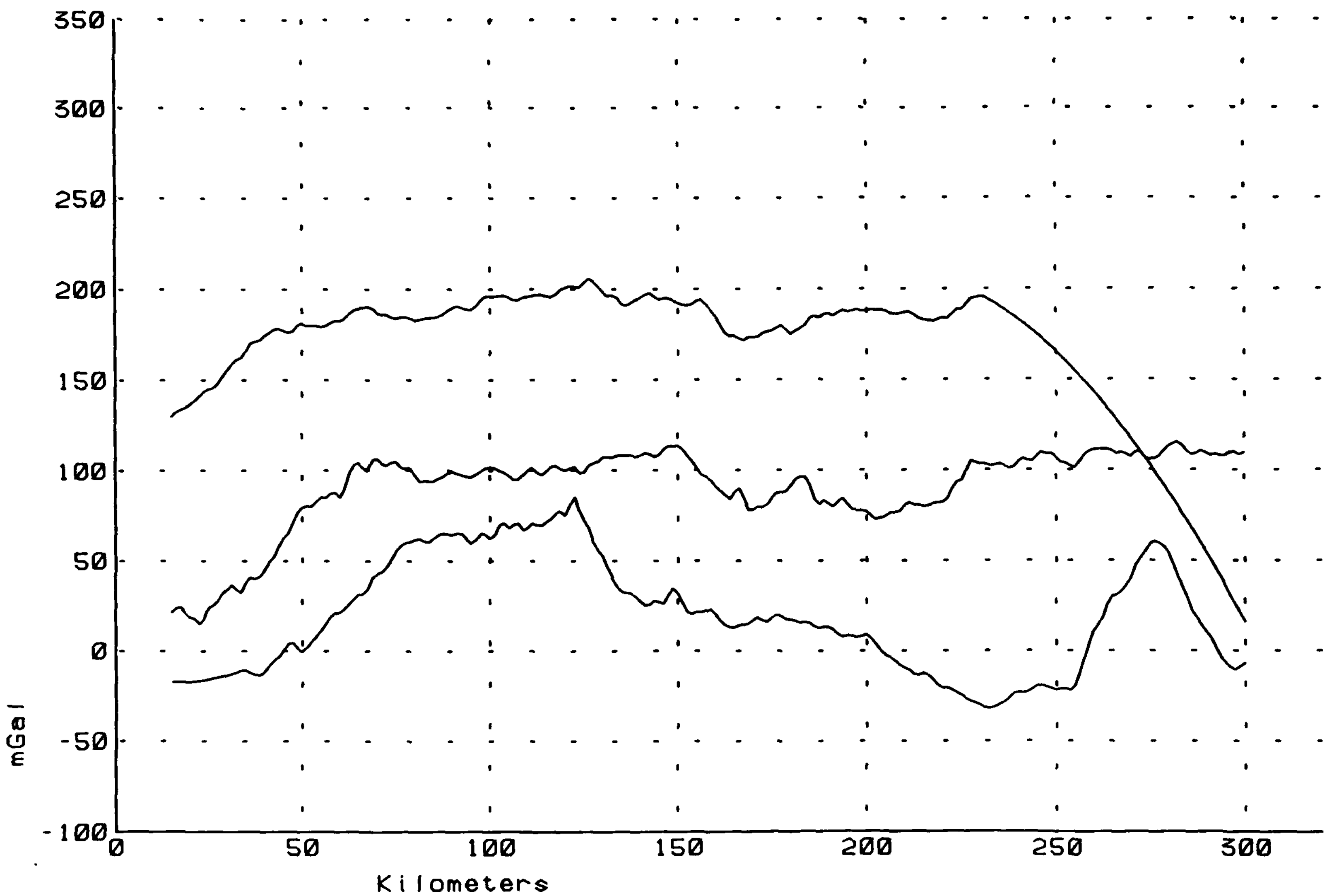


FIGURE 73

Ty EW 26 47 49

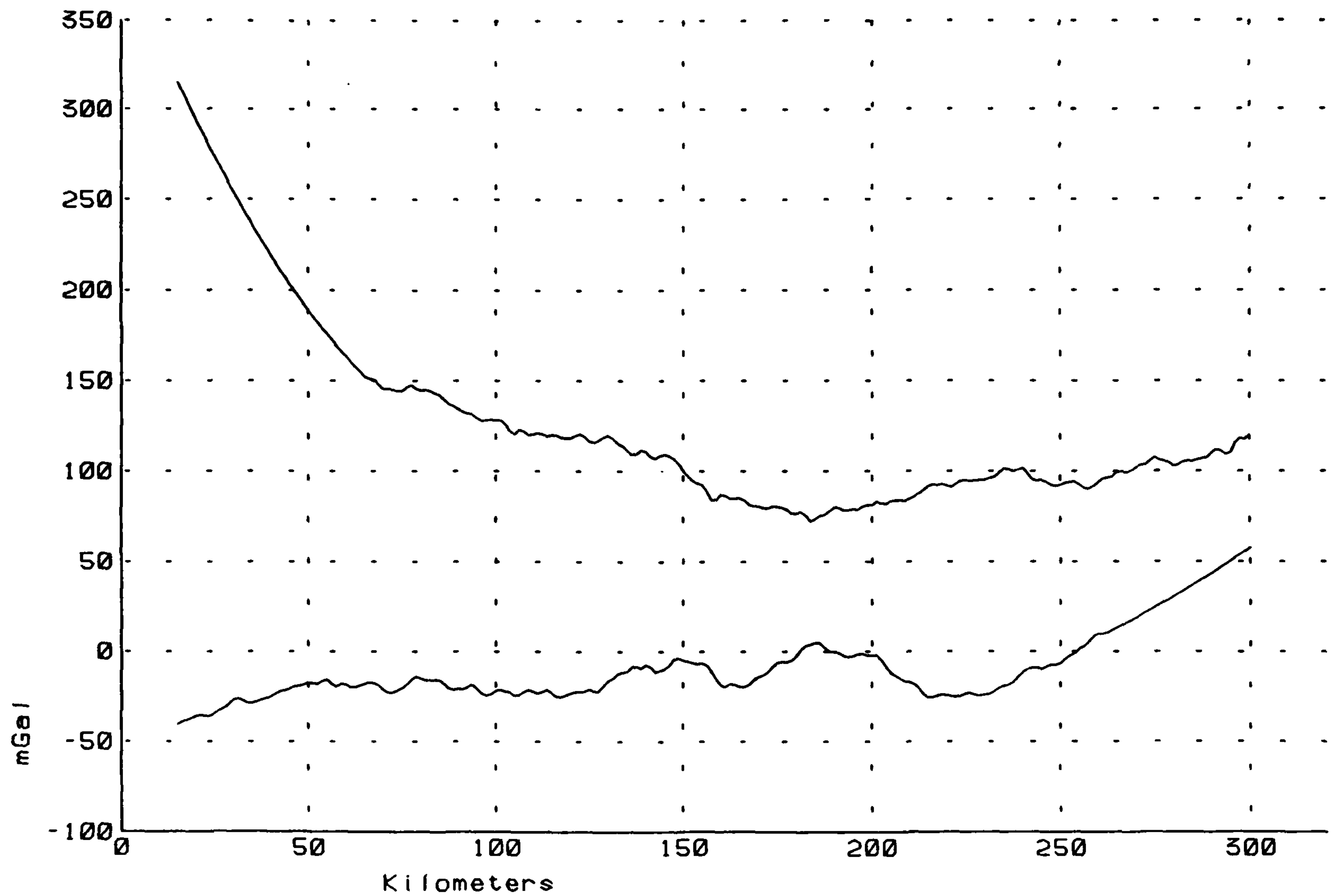


FIGURE 74

Ty EW 53 55

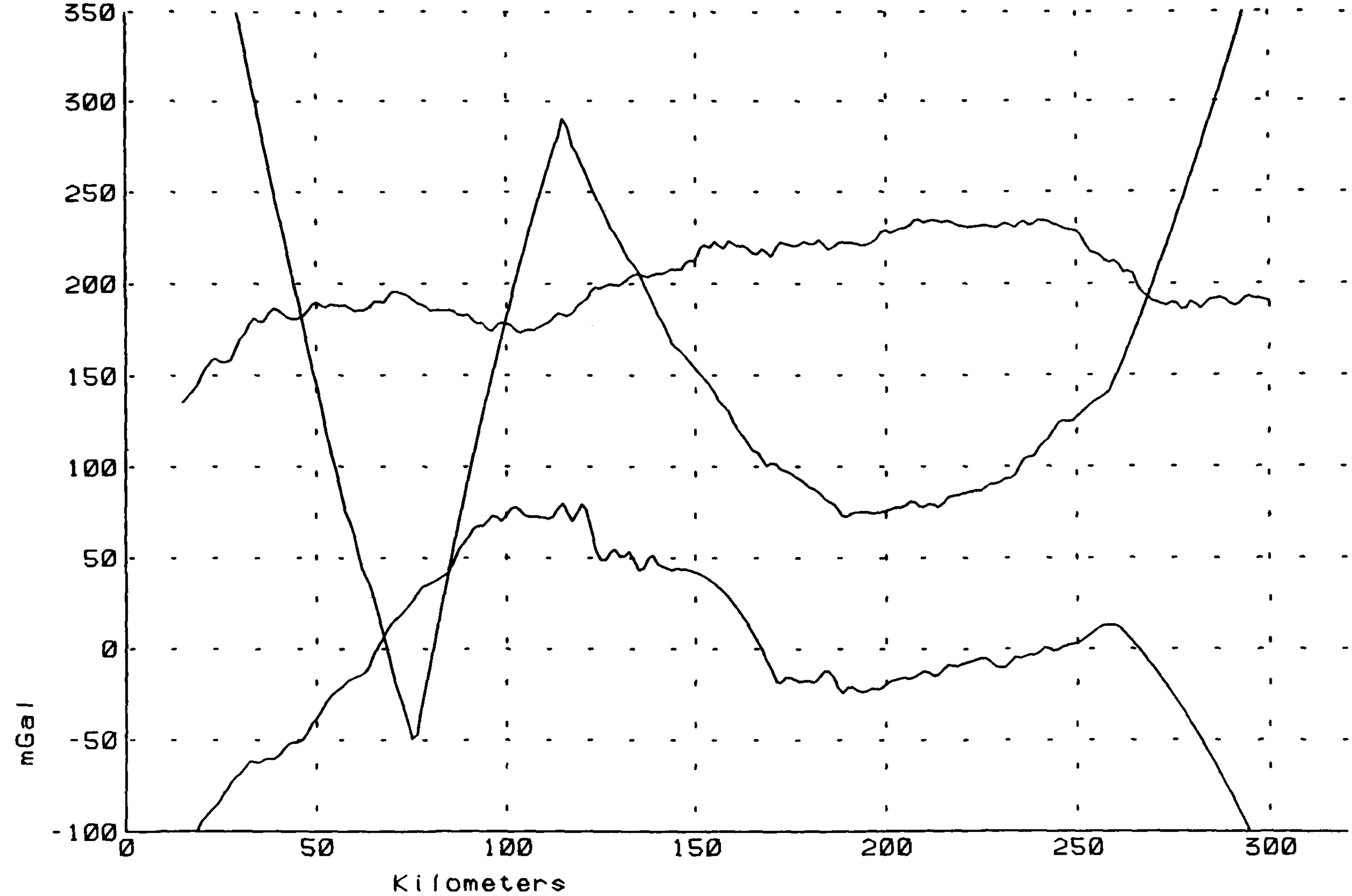


FIGURE 75

Ty EW 57 60 61

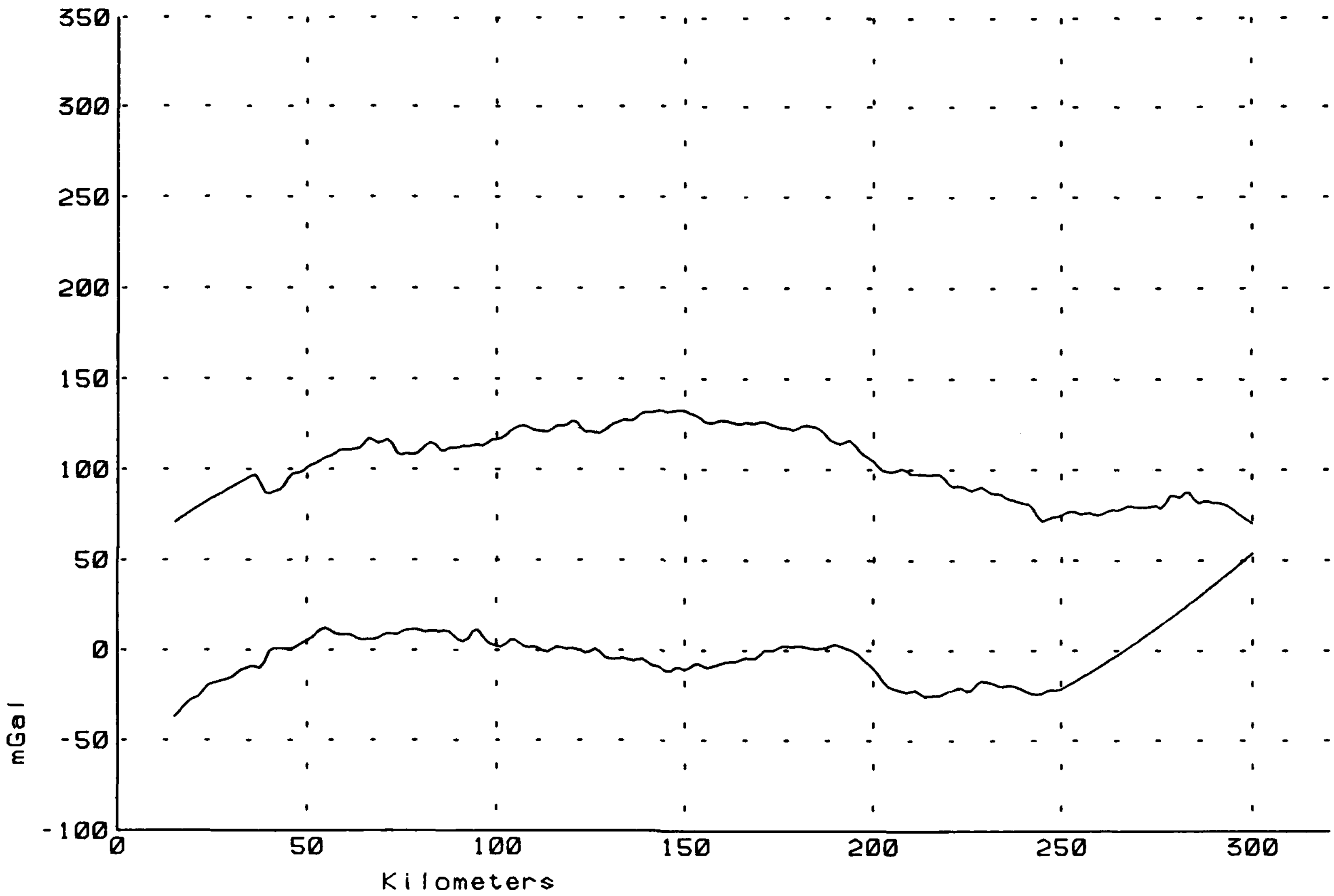


FIGURE 76

Ty NS 11 13

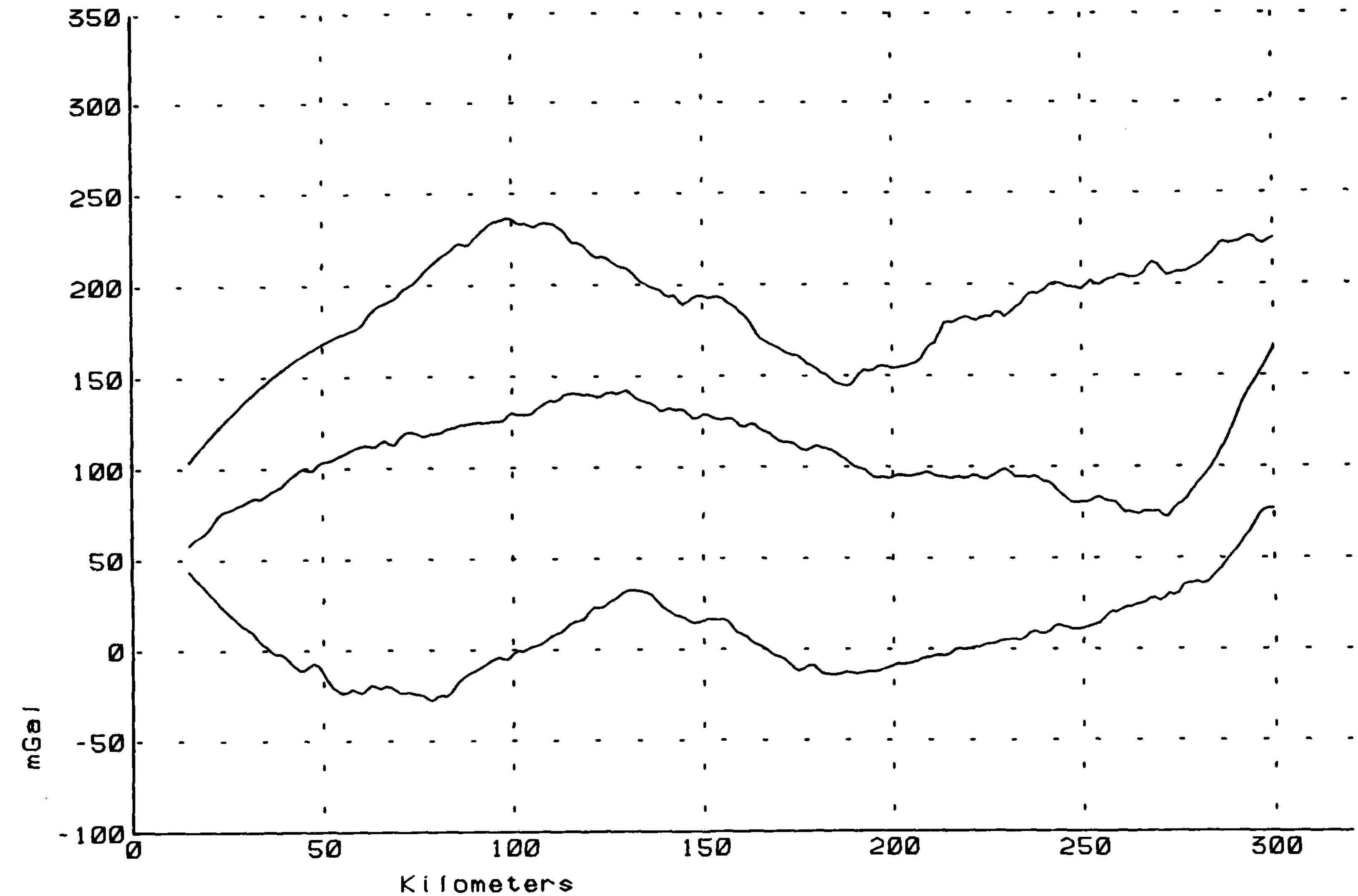


FIGURE 77

Ty NS 28 30 32

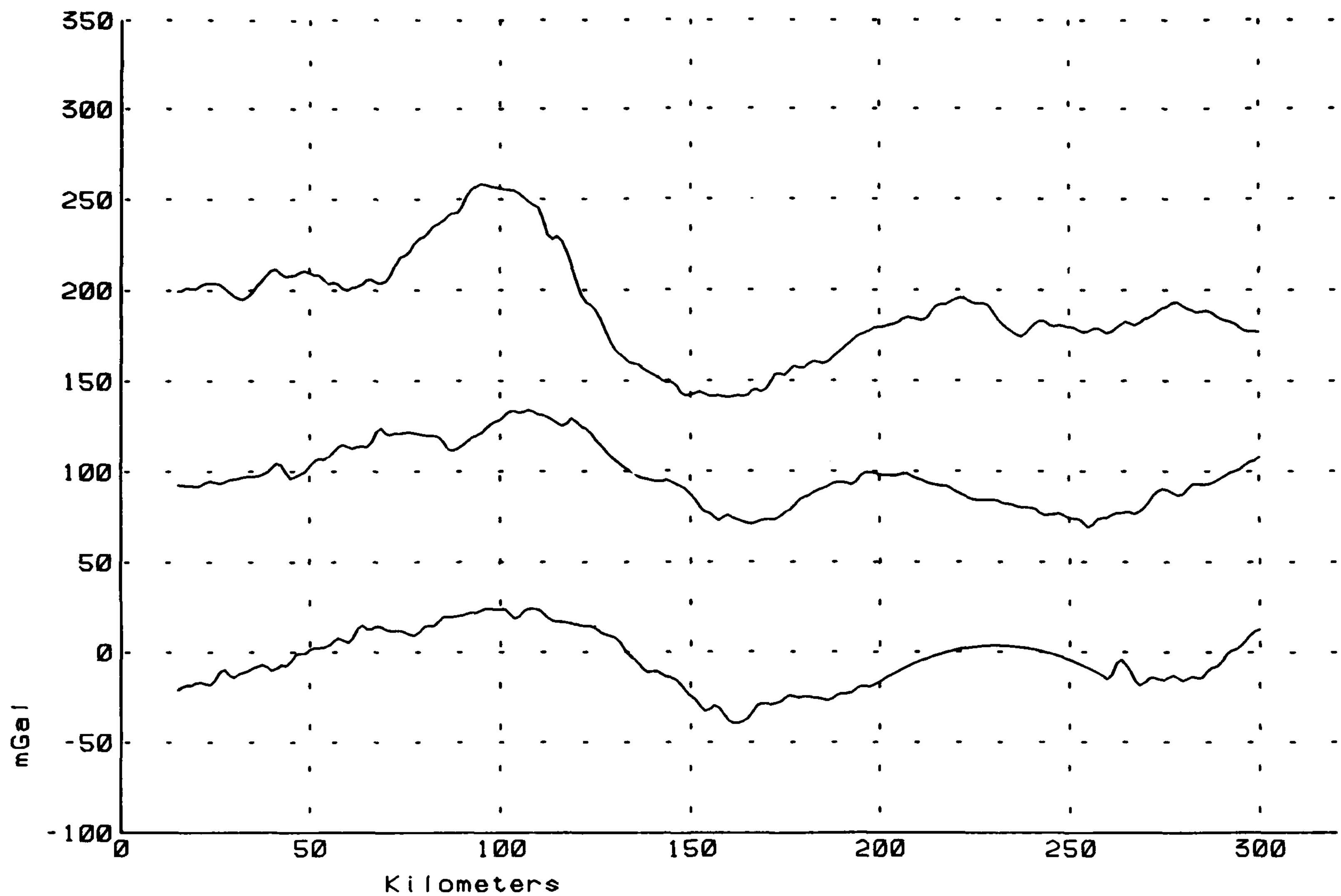


FIGURE 78

Ty NS 35 39 41

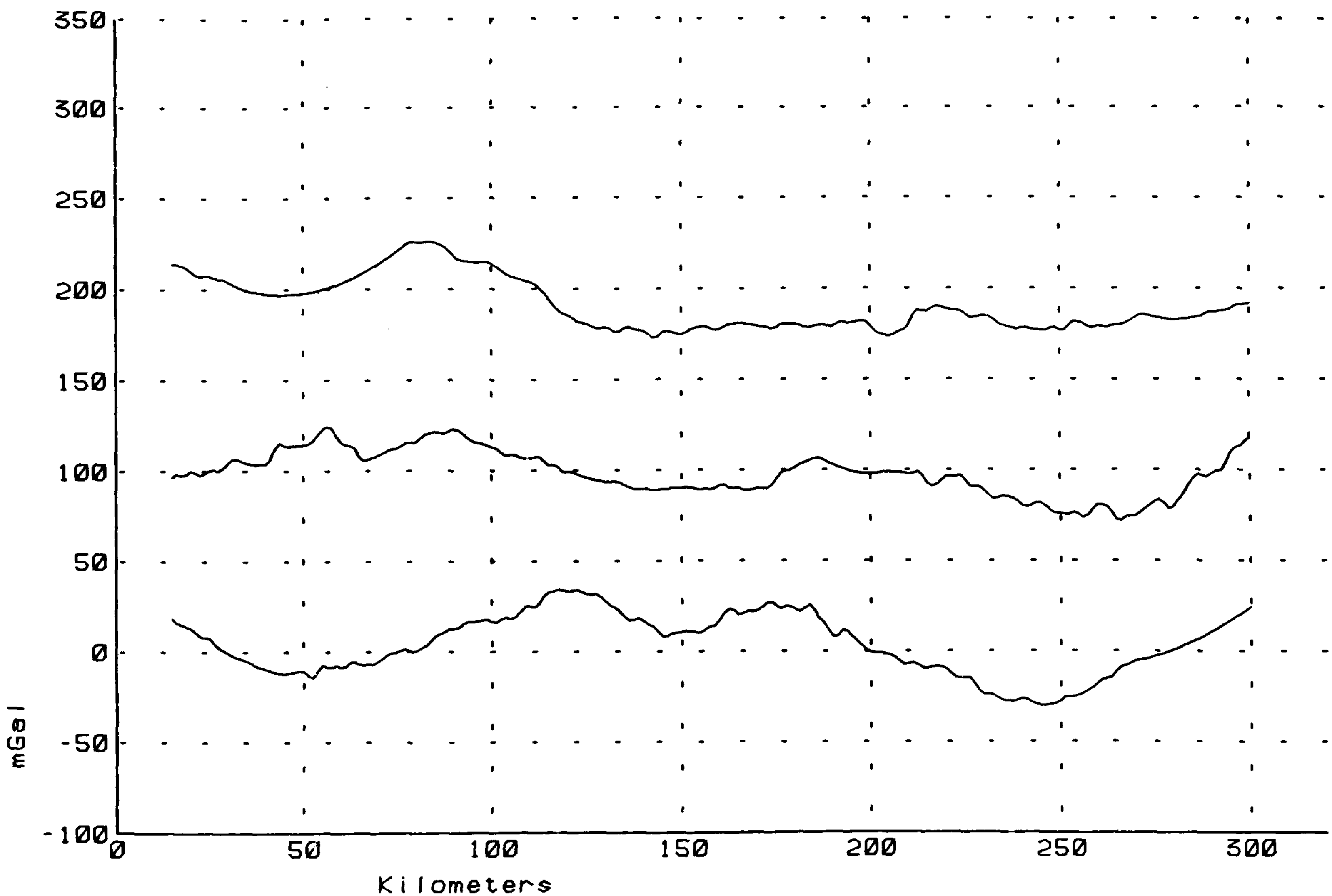


FIGURE 79

Ty NS 42 43 44

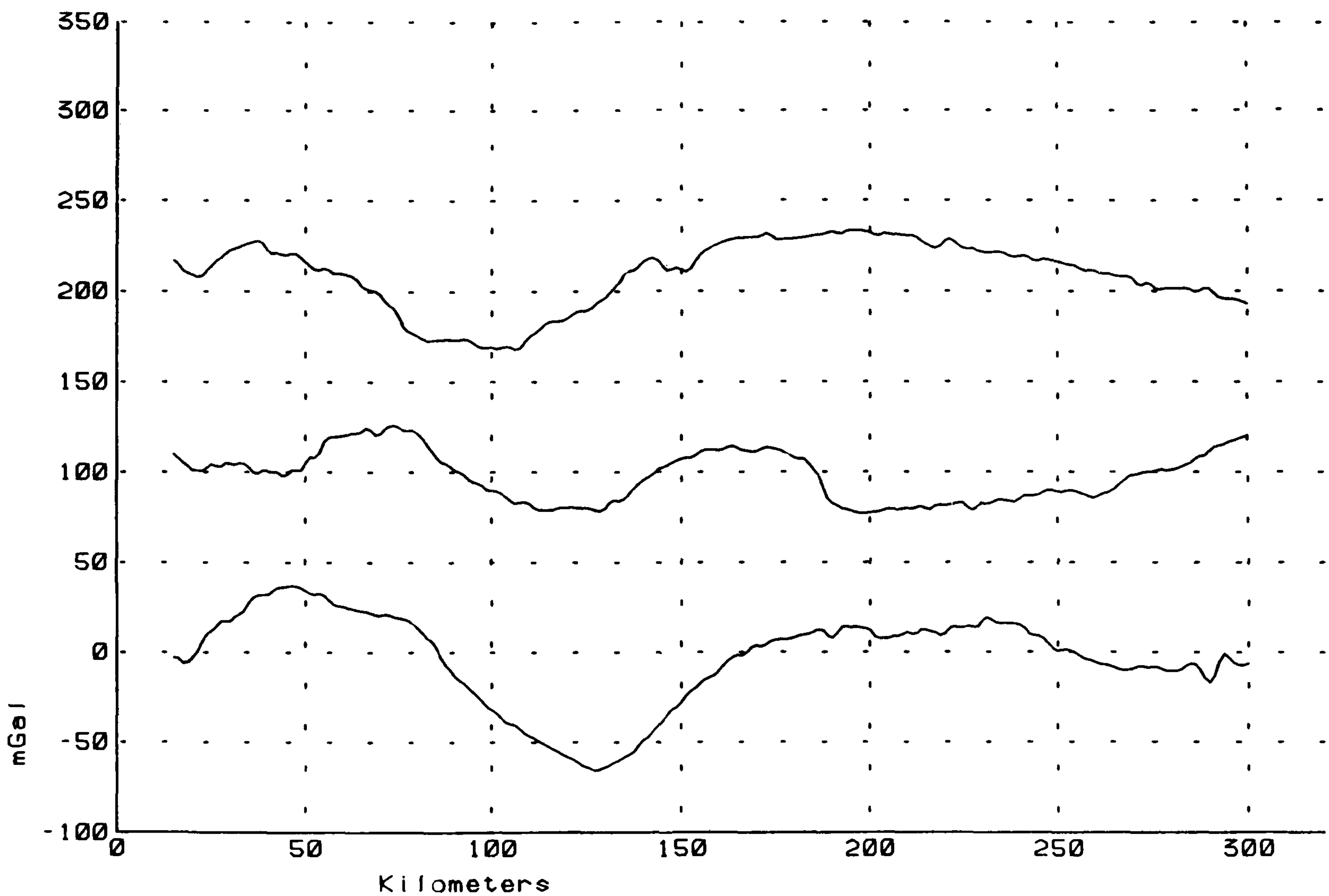


FIGURE 80

Ty NS 46 48 51

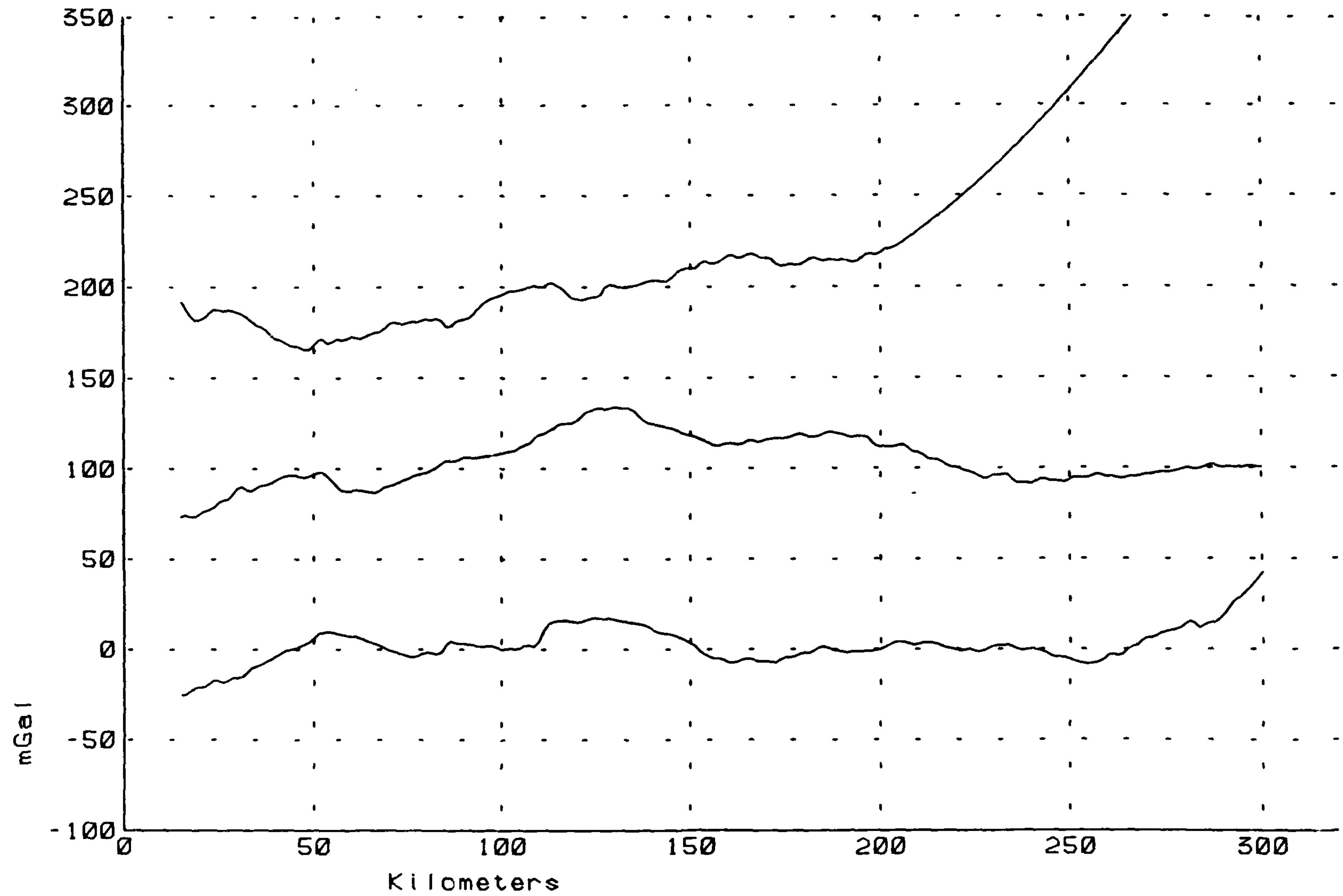


FIGURE 81

Ty NS 53 55 61

6.0 LAND MOBILE GRAVITY SURVEY

Land vehicle testing, was to occur in two phases, with Phase I repeat track testing planned for Western New York. Phase II land vehicle surveys were planned for Oklahoma.

6.1 Test Plan

The test plan for Phase I land described in section 4 of Bell Report No. 6496-928004 "System Test Plan" was not formally conducted in Western New York but several repeat tracks were surveyed in Oklahoma.

The test plan for Phase II land survey is described in section 5 of the "System Test Plan" report.

6.1.1 Local, Road Course, Procedure

Figure 6-1 shows the land vehicle test area in Oklahoma. Routes and ground control points are marked on this figure. Each mission started and ended at the Clinton Sherman Airport. The vehicle parked at each of the ground control points to facilitate a 5th wheel navigation update for both real time and post mission processing.

6.1.2 Data Reduction Requirement

Figure 5-1 is also valid for land vehicle testing except that Stage II is quite different. Details of the Stage 2 processing are described in Report No. 6496-928006 "Technical Report Stage 2 (Land) Post Mission Data Processing. Stage 1 processing differs only in the bandwidth of the demodulation filter as described in Bell Report No. 6496-928006.

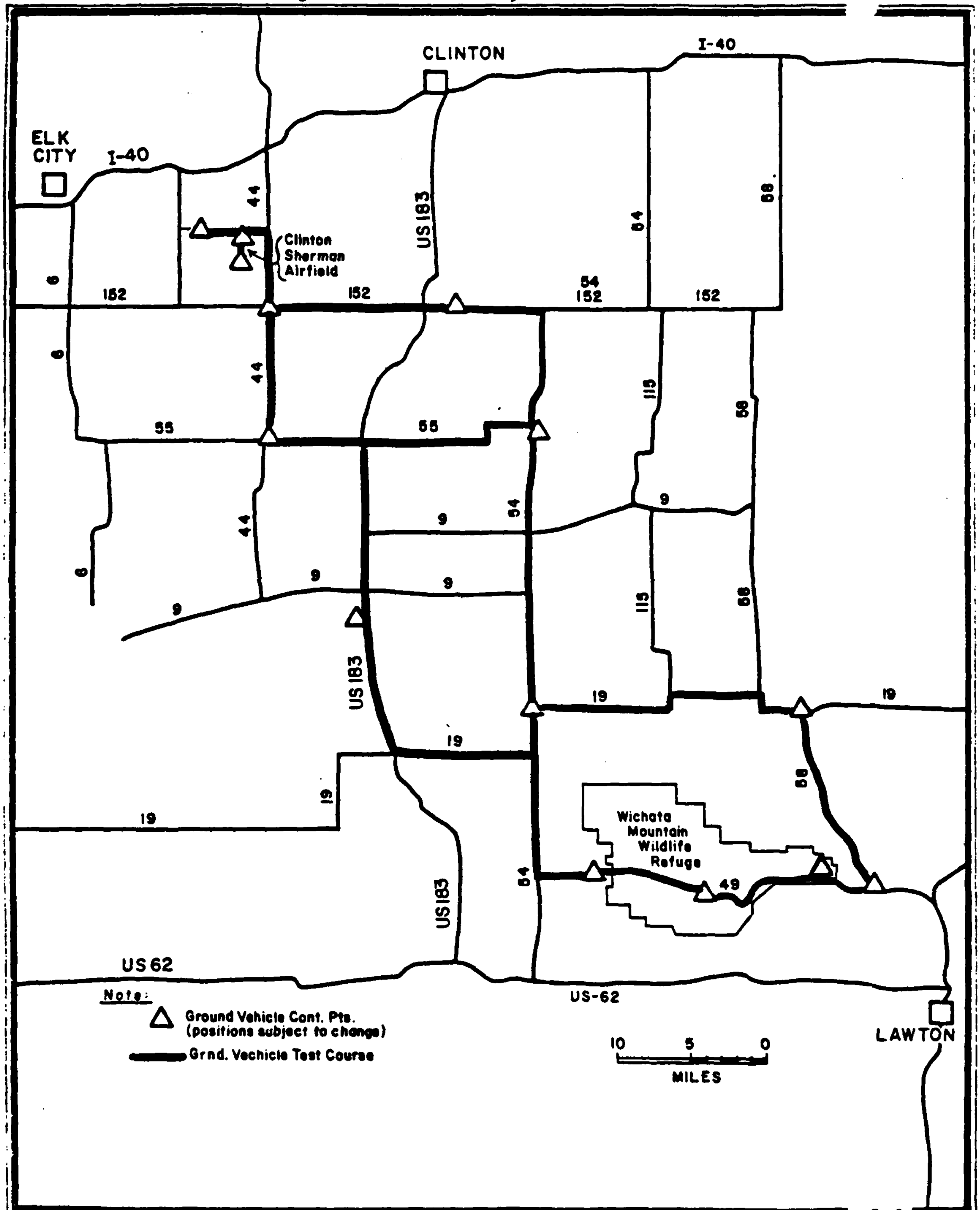
6.2 Conduct of Land Survey

6.2.1 Pre Survey Field Activities

Before driving the GGSS van around the midwest Oklahoma roadways, the designated routes were driven by passenger car to confirm Astro-Geodetic point locations and to establish the stopping and turning maneuvers required. This enabled efficient preplanning of time expenditure and tactics for the van to traverse the routes and stop at the "Astros" for navigation updating. See Figure 6-1.

FIGURE 6-1

GRAVITY GRADIOMETER ground vehicle survey area



6.2.2 Land Survey Operation

Compared to airborne, conducting the land survey operation in Oklahoma was simple and straight forward for the following reasons:

- No aircraft operational contraints imposed (flight clearances, bad weather, aircraft failures, etc).
- No dependency on GPS; 5th wheel Nav-aiding used instead. Surveys could be conducted at any time of day and for any duration.

The entire land survey data collection effort was accomplished in approximately one week, starting immediately after the May 28th departure of the aircraft.

6.2.3 Mileage Surveyed

Figure 6-1 is a road map of the land survey area with bold lines showing the road covered by the survey and triangles showing astro-geodetic survey point locations. In all, nearly 400 miles of roads were traversed.

Surveys were conducted in daylight hours. So little vehicular traffic was encountered during daytime that it was not considered necessary to survey during the night to avoid it.

The test plan called for three separate surveys, each starting and ending at Clinton-Sherman, to form three closed-loop courses. The first loop was approximately 65 miles total length, the second, 115 miles long and the third 200 miles long. (See Figures 6-2, 6-3, and 6-4). Note that all loops share some common roadway so that repeat traverses were obtained in those areas. All surveying was conducted at 20 to 25 MPH, with stops at each astro location encountered for position & velocity updates to the navigation system. Stop duration was typically less than 2 minutes.

6.2.4 Problems and Accomplishments

All the approximately 400 miles of planned road course survey was accomplished without incident. All data was recorded on magtape and dispatched to Bell (Wheatfield, NY facility).

Upon land survey completion, the van commenced to visit each of the eight (8) astro geodetic locations near the periphery of the 315KM x 315KM airborne survey area. The plan was to survey the gradients for about 2 miles north/south and 2 miles east/west around each astro to assist in upward continuation of the astro gravity points used for reduction and evaluation of airborne survey data.

The eight astro locations represented considerable distances from Clinton-Sherman (relative to the land survey road course) and so took a fair bit of time to get to. Gravity was not surveyed during the trip to an astro location and therefore the van was driven at approximately 40 to 50 MPH where the roads were straight and smooth.

GGSS equipment failures were encountered after visiting three of the eight astro locations, probably due the increased vibrations in the van during the higher speed, long duration transits between astros. The failures occured in the electronics racks No's 1 and 3, specifically in the GGIB (Interface Buffer) and LCMPs (GGI Loop Controls). The failures could not be easily repaired in the field. Given the condition of a game but exhausted team of field engineers who had, for the most part, spent 2½ months supporting a 7 long day per week operation, the Oklahoma survey effort was terminated. The C-130 from Southern Air Transport was re-enlisted for one day to pick-up the GGSS and return it to the Bell plant.

Figure 6-2
1st Road Course Loop
(5 miles around)
GGSS Oklahoma Land Survey

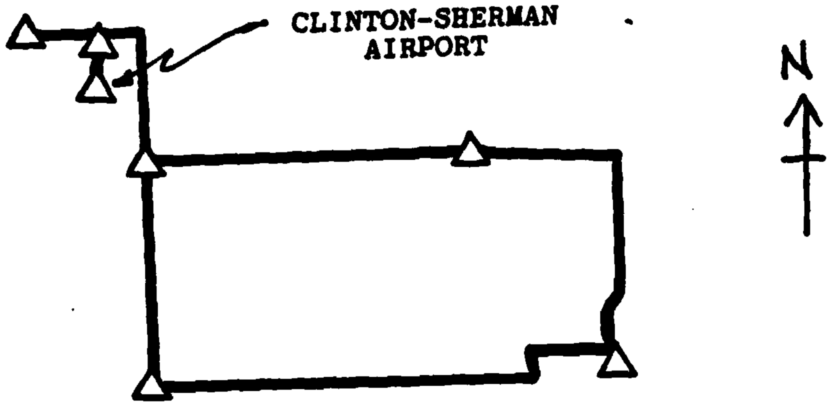


Figure 6-3
2nd Road Course Loop
(115 miles around)
GGSS Oklahoma Land Survey

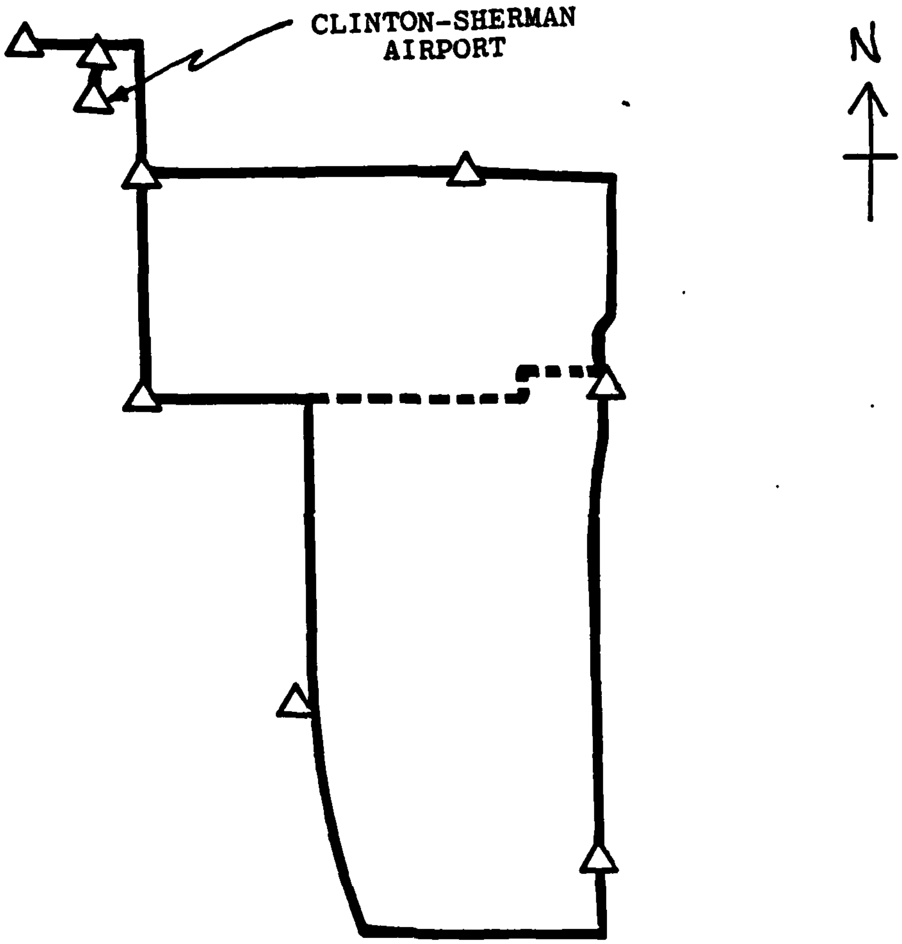
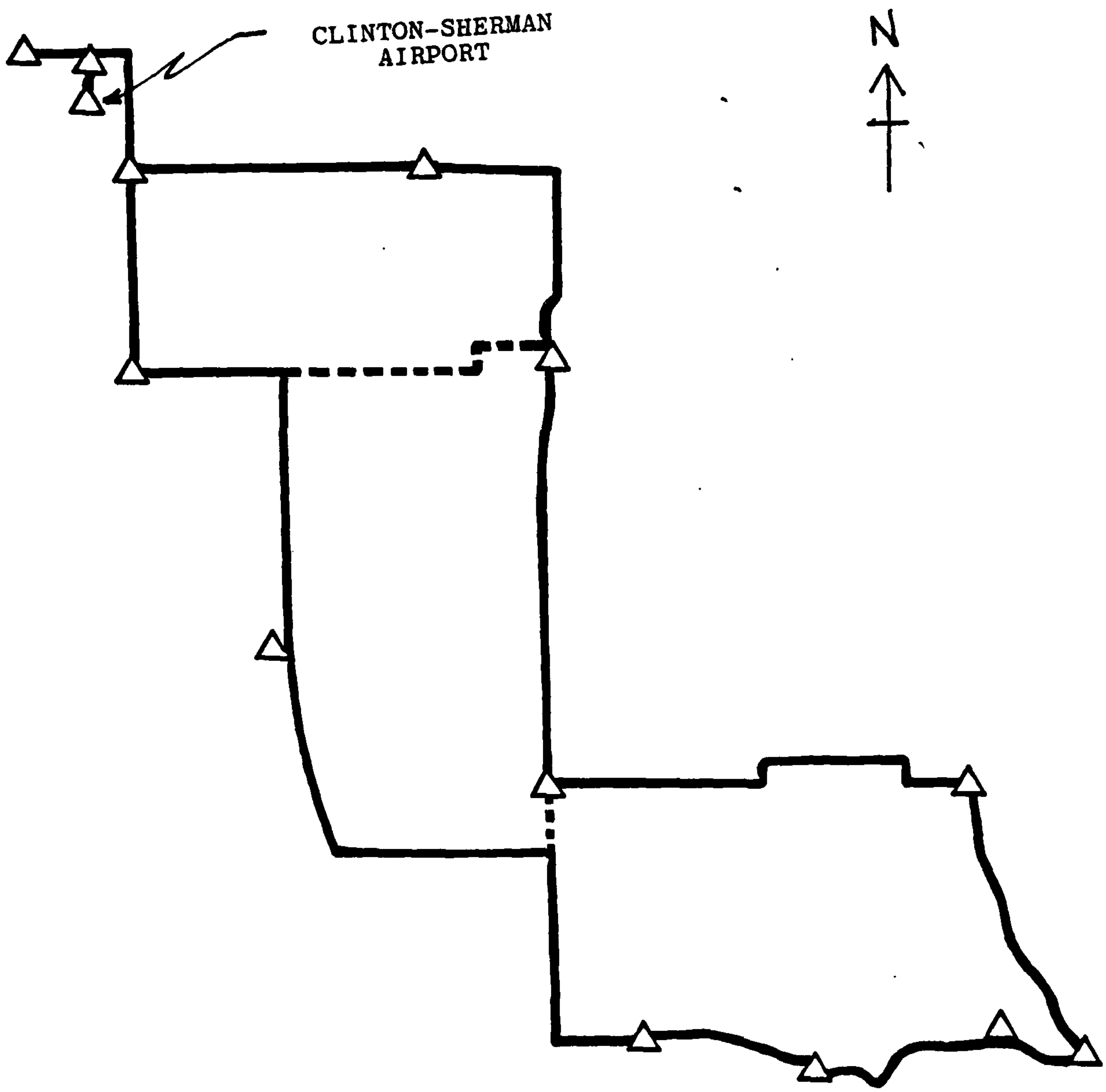


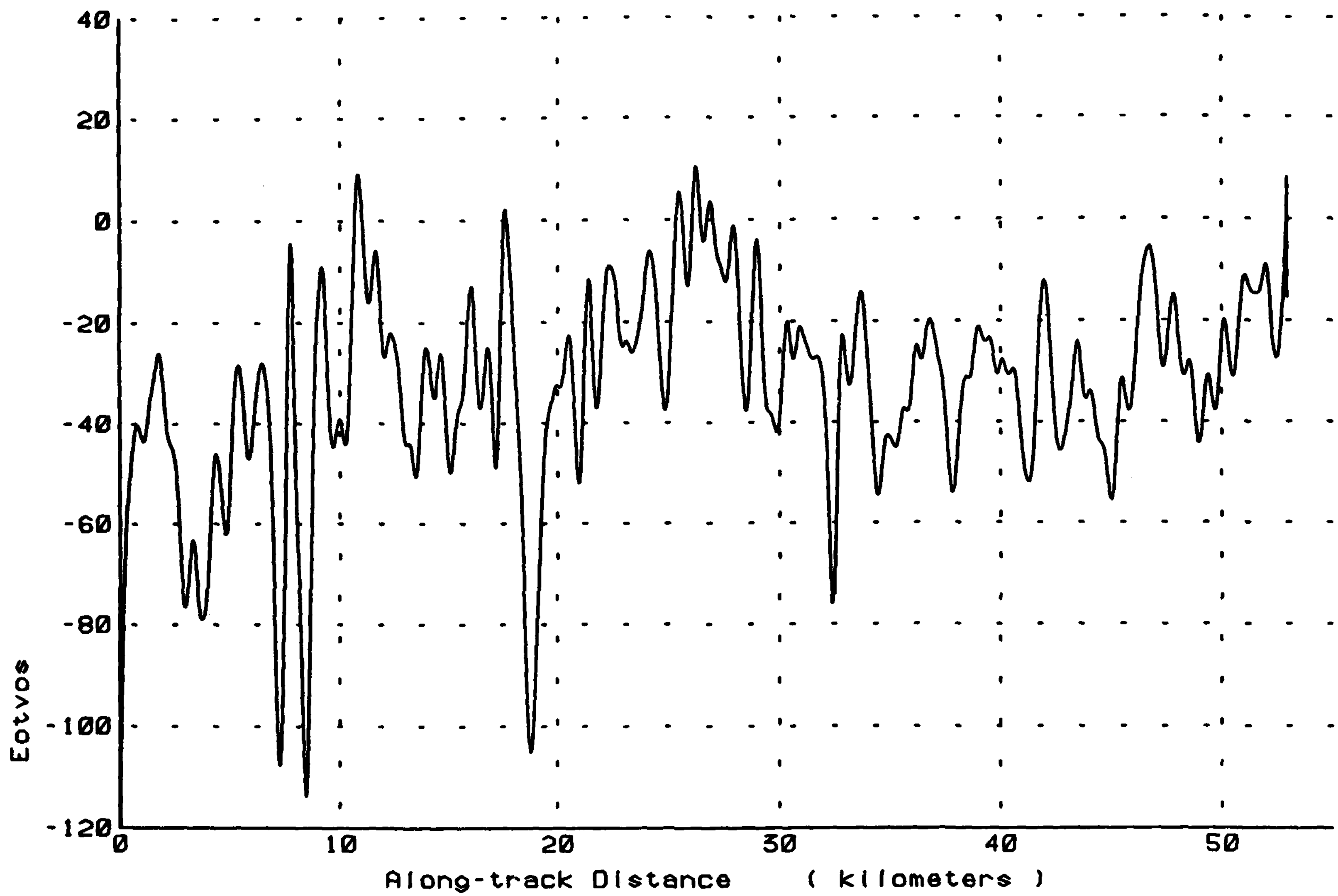
Figure 6-4
3rd Road Course Loop
(200 miles around)
GGSS Oklahoma Land Survey



6.3 Data Reduction

In Section 2 of this report we pointed out that only two repeat track sections of land vehicle data were analyzed, namely the southbound route from astro - location No. 7 to astro location No. 9 (see Figure 2-3). Filtered NED gradients for these two tracks are plotted in Figures 6-5 through 6-14.

The results of a straight integration of these measured gradients using tie point disturbance vector values at astro-locations 6, 7, and 9 to control gradiometer bias, are presented and discussed in section 2.3 of this report.



Txx

FIGURE 6-5

Oklahoma Land Survey 6 June 87

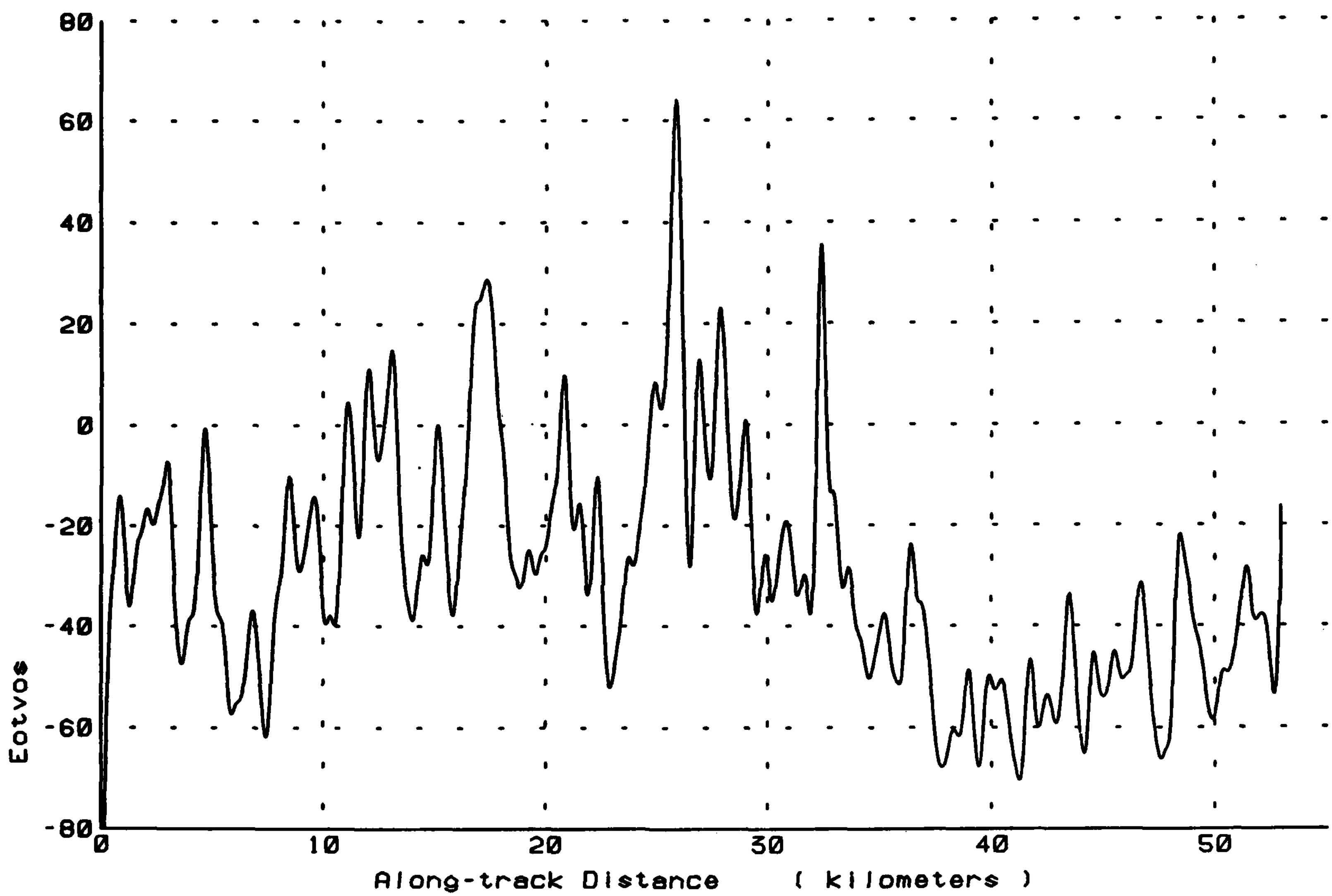
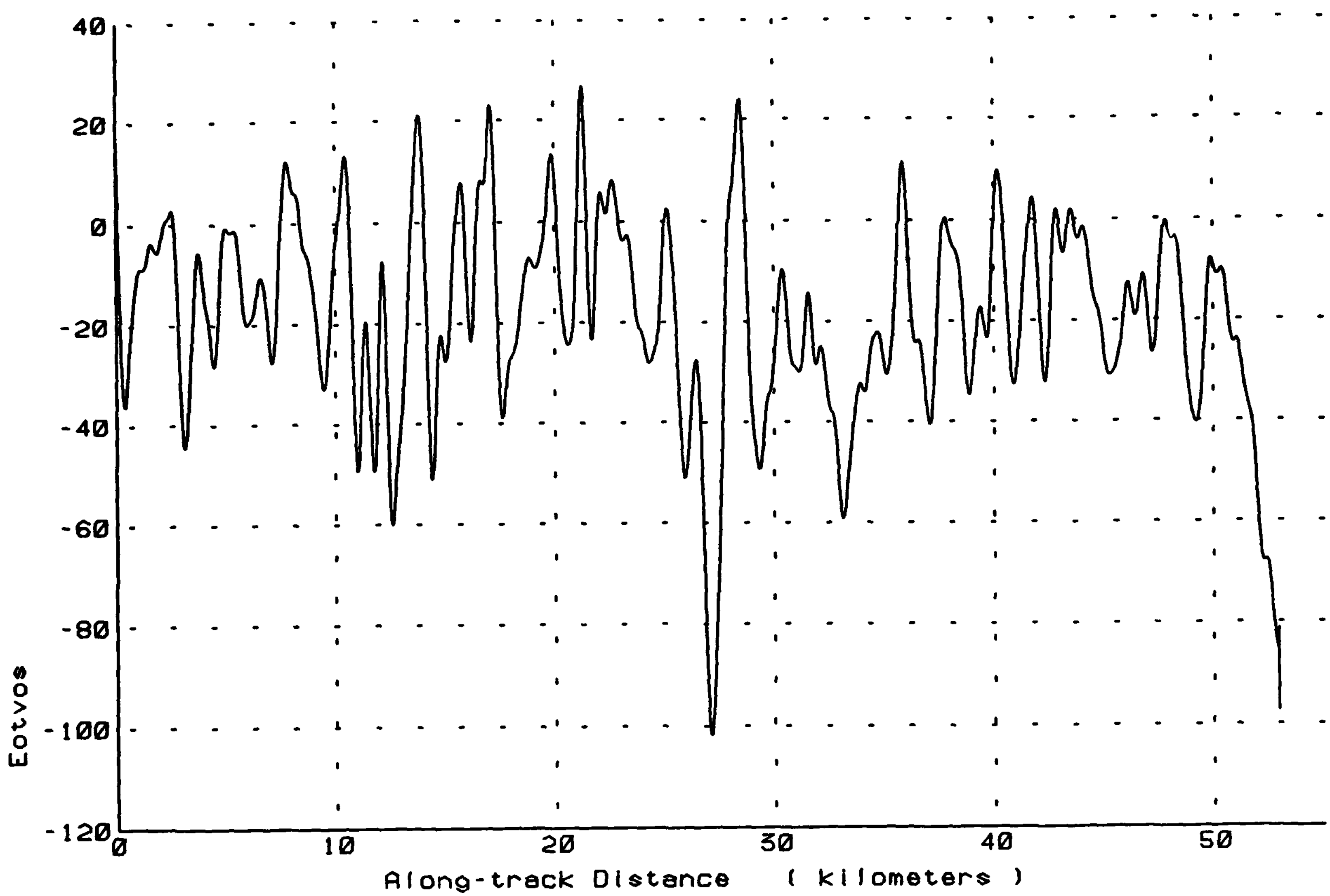


FIGURE 6-6

Txy

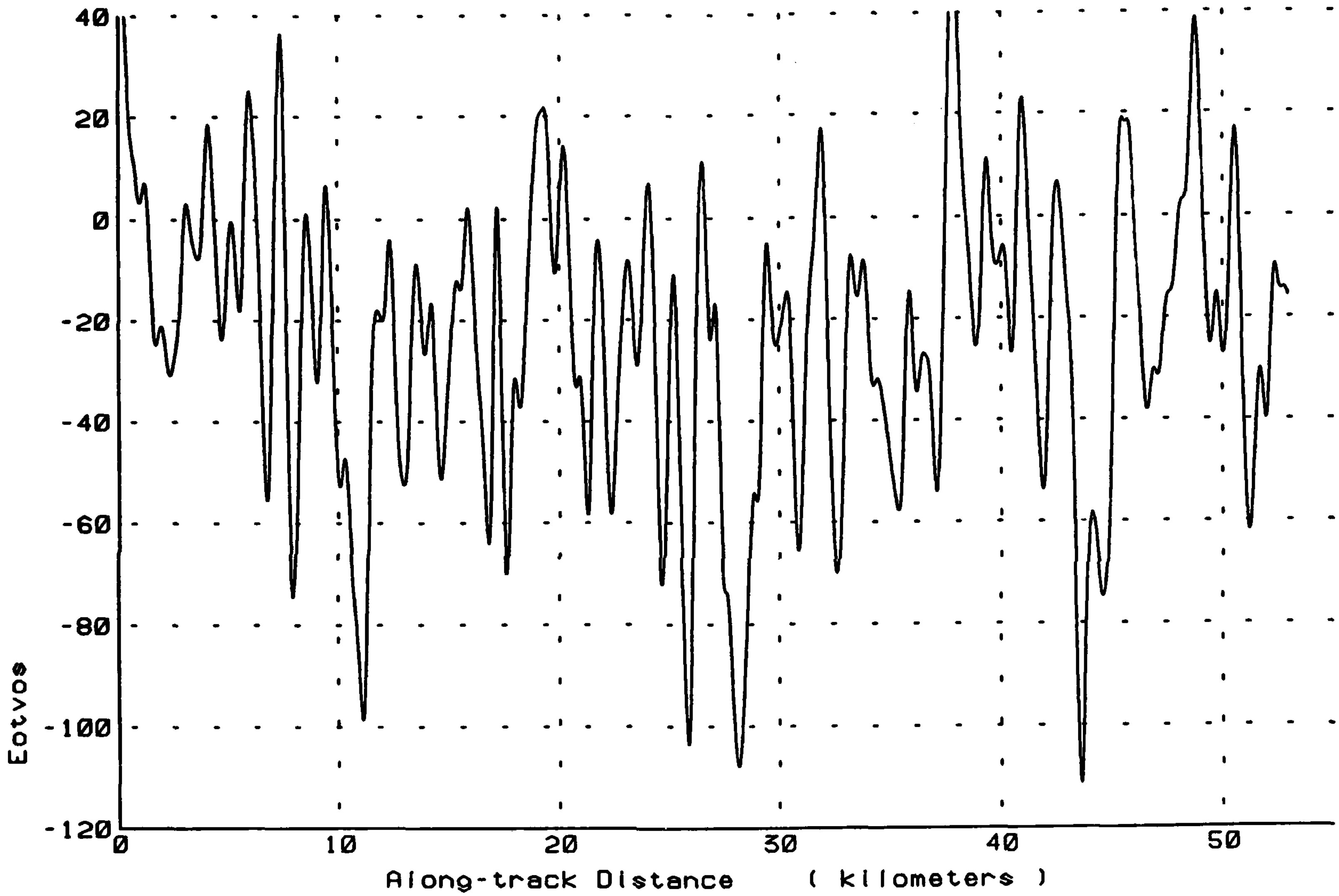
Oklahoma Land Survey 6 June 87



Txz

FIGURE 6-7

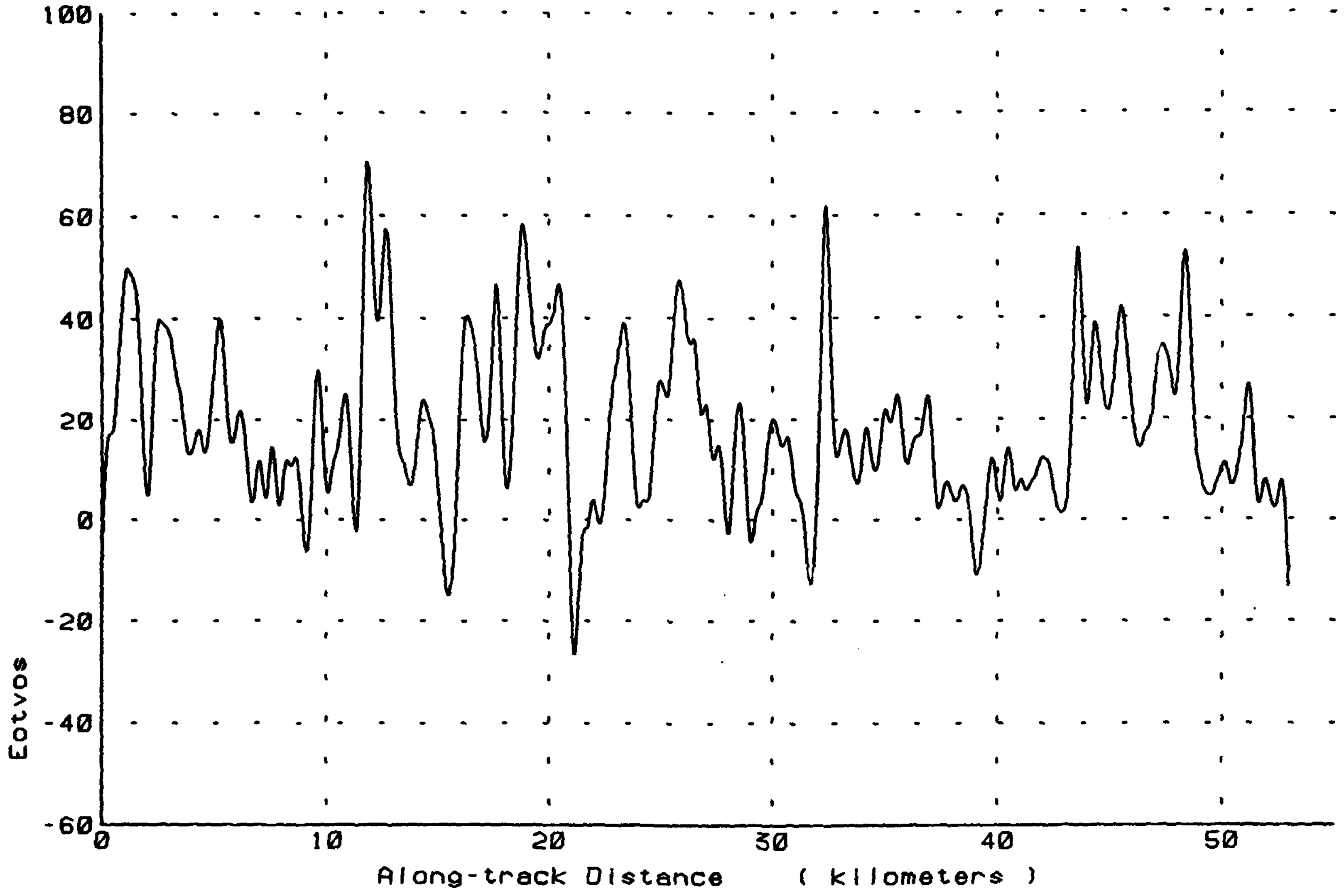
Oklahoma Land Survey 6 June 87



Tyy

FIGURE 6-8

Oklahoma Land Survey 6 June 87



Tyz

FIGURE 6-9

Oklahoma Land Survey 6 June 87

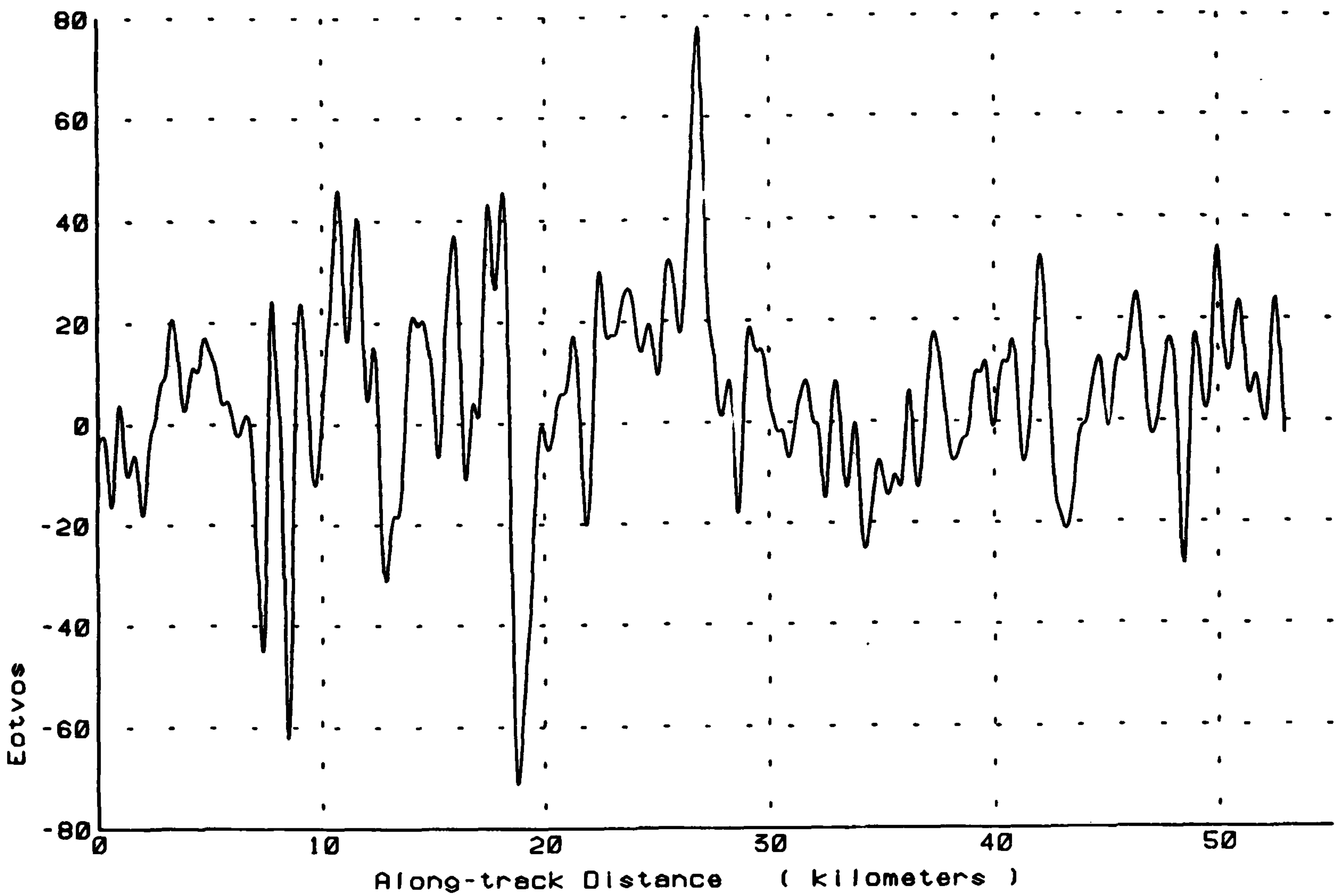


FIGURE 6-10

Txx

Oklahoma Land Survey 9 June 87

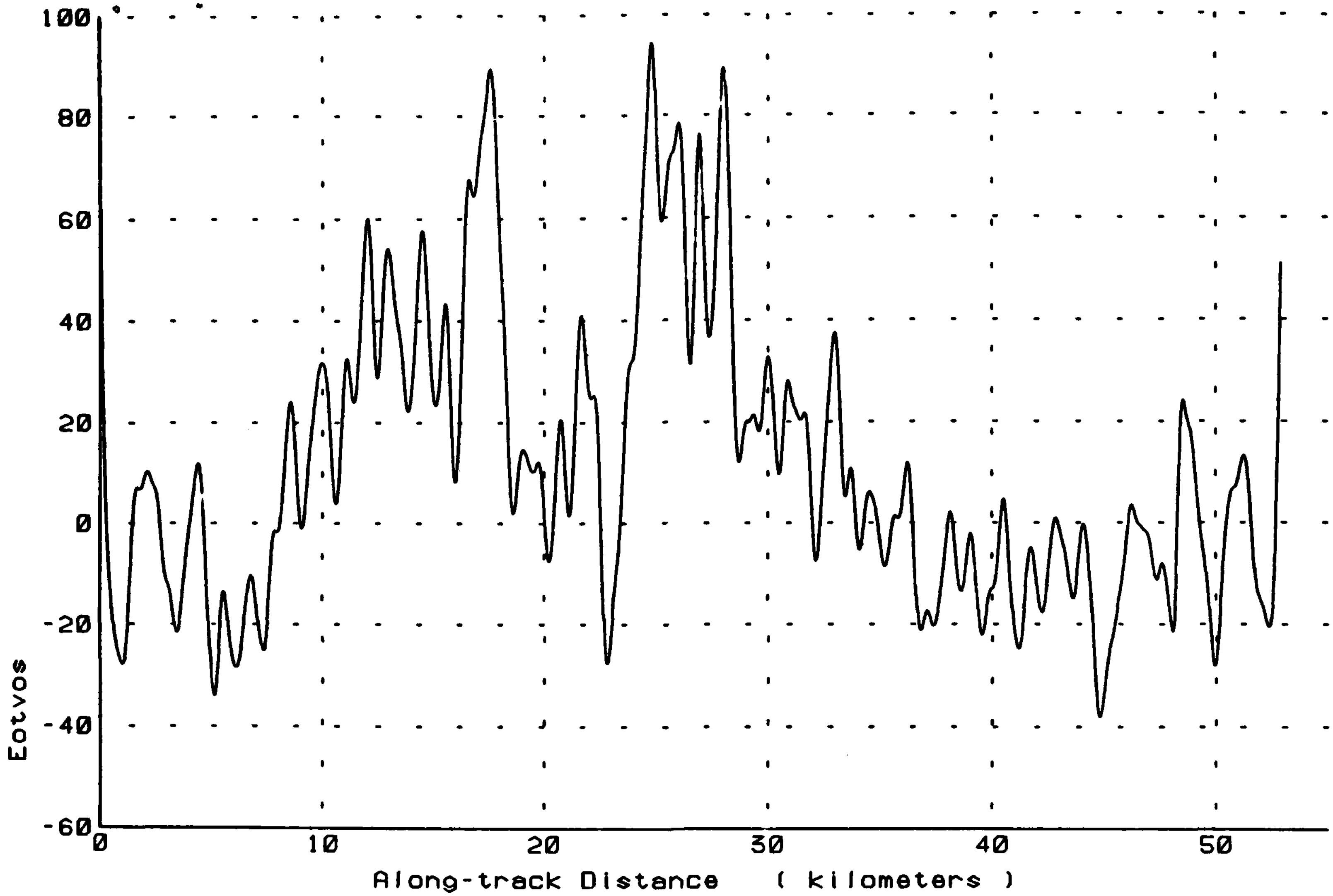


FIGURE 6-11

Txy

Oklahoma Land Survey 9 June 87

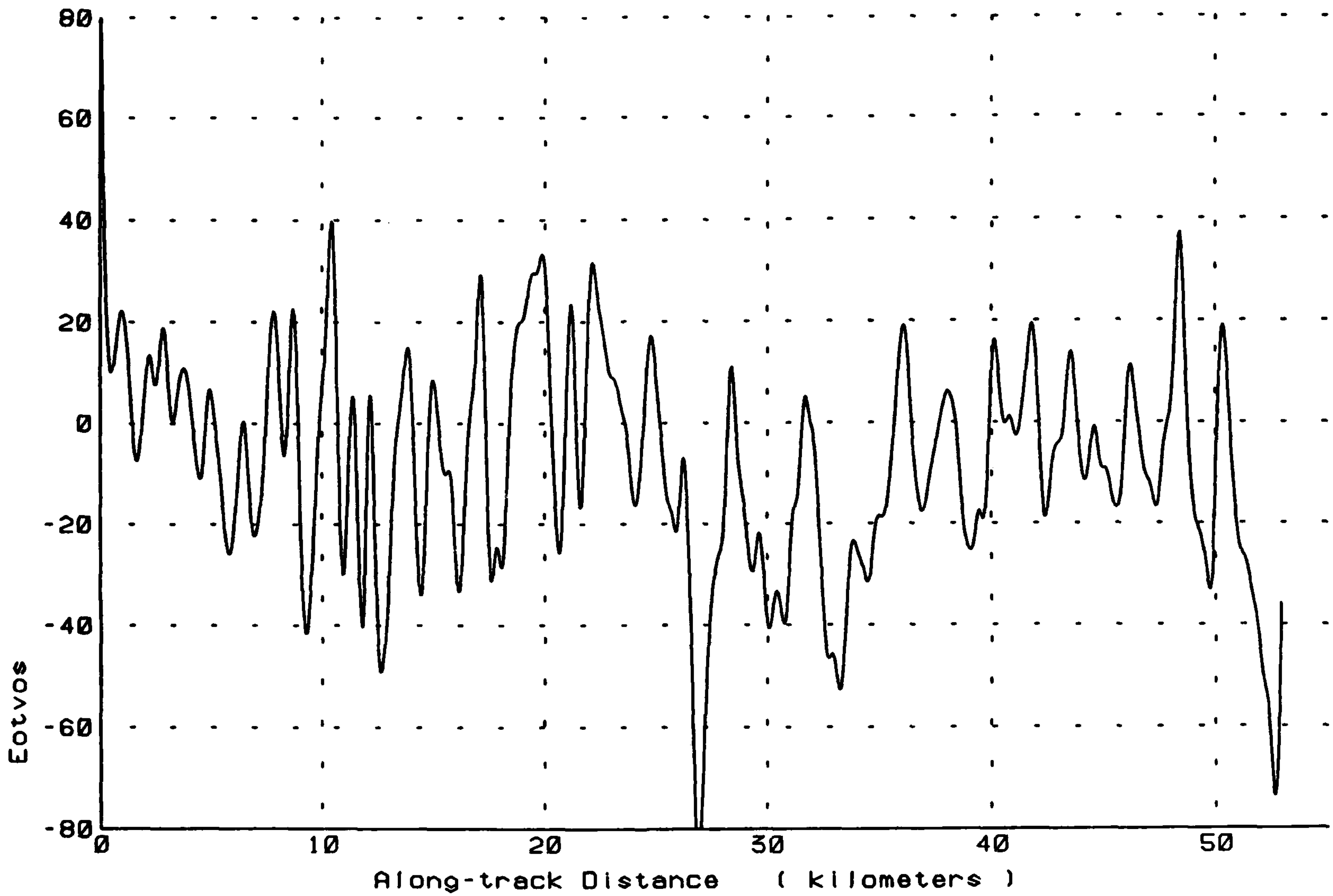


FIGURE 6-12

Txz

Oklahoma Land Survey 9 June 87

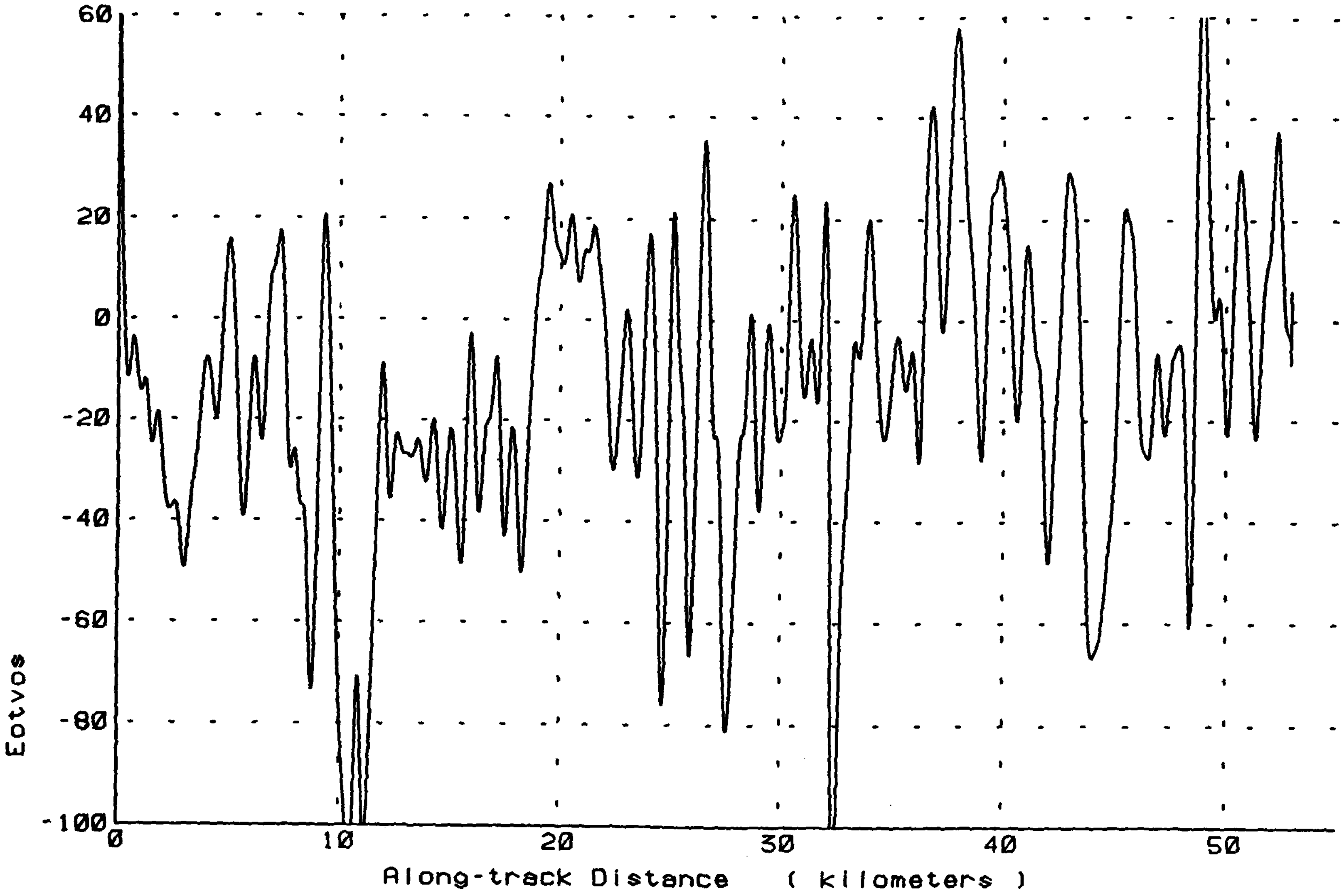
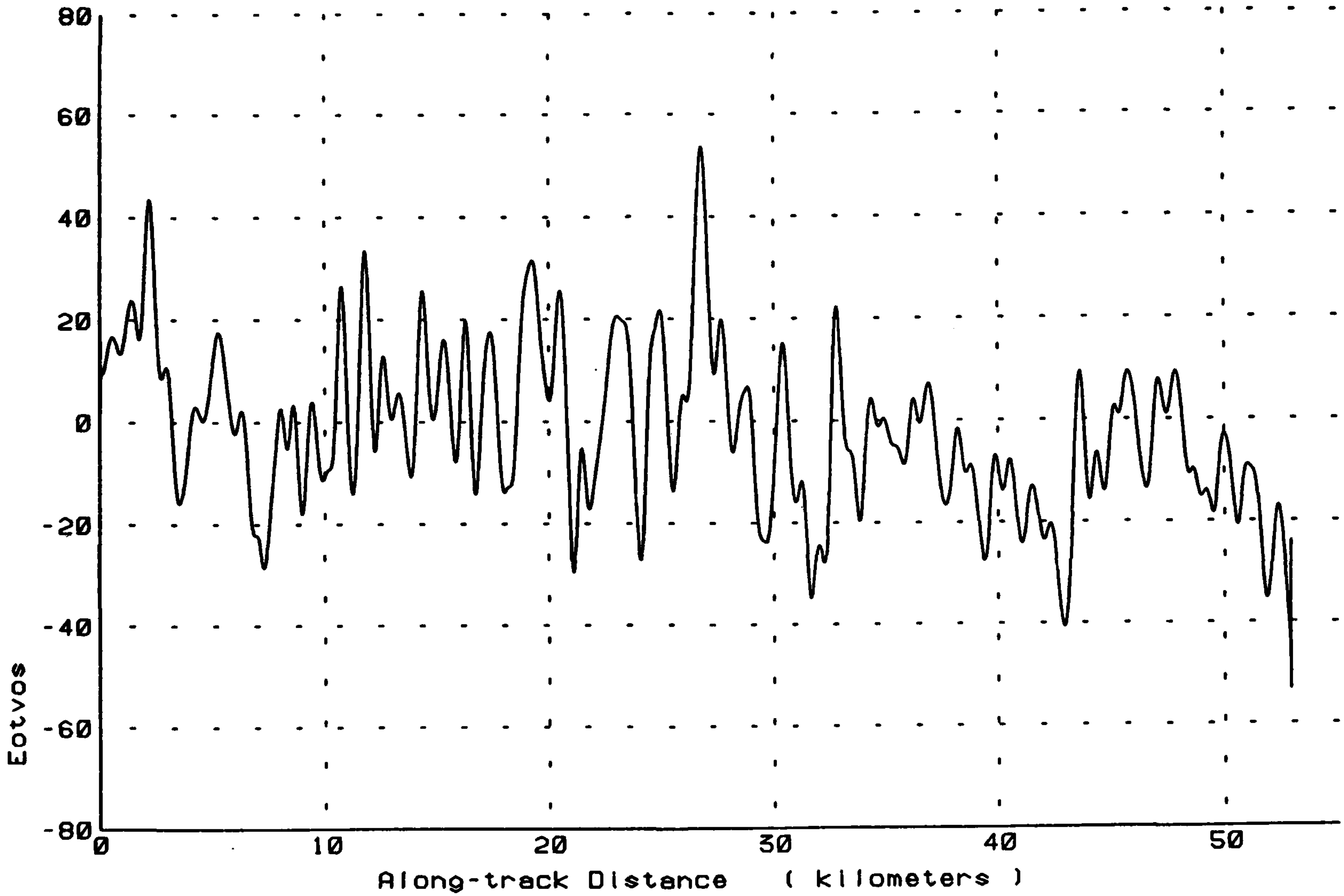


FIGURE 6-13

Tyy

Oklahoma Land Survey 9 June 87



Tyz

FIGURE 6-14

Oklahoma Land Survey 9 June 87